Experimental Investigation of Effects of Wing Camber on Drag for a Bio-Mimic MAV Flapping Wing

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ABSTRACT

Flapping-Wing Micro Air Vehicles (FW-MAVs) are small hand-held flying vehicles that can maneuver in constrained space owing to its lightweight, low aspect ratio and can fly in low Reynolds number environment. In the present study, the aerodynamic characteristics such as time-averaged lift camber wings with different five wind tunnel models having 6, 9, 12, and 15% camber were developed are compared with those of a flat wing to assess the effects of camber wing on the aerodynamic performance for flapping flight applications. The experiments were performed in an open circuit wind tunnel with of non-return airflow with a test section of (0.3m x 0.3m) and capable of speeds from 0.5 to 30 m/s. The time-averaged lift as functions of advance ratio of the flapping motions with respect to the incoming flows are measured by using a strain gauge balance and KYOWA PCD-300A sensor interface data acquisition system. It is found that camber would bring significant aerodynamic benefits when the flapping flight is in unsteady state regime, with advance ratio less than 1.0. The aerodynamic benefits of camber are found to decay exponentially with the increasing advance ratio. Cambered wing show significantly higher lift in comparison with the flat wing.

Keywords: *Flapping wing, camber, free stream velocity, frequency, aerodynamic efficiency*

Introduction

Bio-mimicry or bio-inspiration, is a method of solving engineering problems by learning or 'mimicking' phenomenons found in nature. One of example of bio-inspiration application is in solving design problems of Micro Air

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ISSN 1823- 5514, eISSN 2550-164X

Received for review: 2017-02-22
Accepted for publication: 2017-10-10
Published: 2018-04-15

Vehicles (MAVs). MAVs holds multiple engineering problems due to its small size, since the definition of MAVs is an aircraft with a wing span of 15cm or smaller. This small size means that, in a fixed wing solution, it is difficult for the wing area to be big enough to generate higher lift without having a chord length that is too long that and creating too much drag [7]. It is also difficult to have a rotary wing solution for MAVs since its small size means that the aerodynamics will be complex enough that stability can be an issue. This means that the solution for a maneuverable and sustainable MAVs may lie in flapping wings design.

One of the reasons why flapping wings can be a solution for MAVs is because flapping wings can produce maneuverability close to a rotary wing while still have the efficiency and stability of a fixed wing, and these attributes are important since power can be a limitation for MAVs since it is small and maneuverability is also important since MAVs are expected to fly in small areas. Flapping wings are not normally found in man made aircrafts, but instead are more commonly found in nature, and in nature there are three main groups of flyers, each have their own advantages and disadvantages.

Each of the flying groups can be characterised by its flight state regime. According to Ho et al. [12], there are two types of flying regimes for a flapping wing, which are; Quasi-steady state regime and unsteady state regime. A quasi-state regime is where during a flapping wing flight, the wing flaps at a lower frequency, but the forward flight of the wing is relatively faster. The first groups of flyers that flies at this flying state regimes are birds. Birds have large wings and are generally more efficient and create less noise. This is because of birds usually rely more on soaring flight to travel long distances and flap at a relatively low frequency. Large birds are also known to travel long distances at a flapping frequency of zero, this flight pattern is known as soaring flight. However, birds usually are less maneuverable which is the reason why birds are rarely found in indoor areas when in nature.

Unsteady state regime however, is defined as the flapping wing flaps at a higher frequency but have a relatively slower forward flight. The second type of flyers that flies at this flight regimes are insects and certain types of small birds (like the humming bird). Insects are known to fly at a higher flapping frequency while have a slow forward movement and sometimes insects are also known to fly without any forward movement at all. This type of flying pattern is called hovering flight and are not observed in large birds. Insects, when compared to birds are more maneuverable and can fly in small areas and even hover for a long time. This is evident since insects are more commonly found indoors and can fly and hover close to an object without losing control or even disturb the object. However, insects have a higher flapping frequency which means that insect flights are less efficient and this is the reason why insects are rarely found to migrate to faraway places or fly long distances when compared to birds. Higher flapping frequency also means that insects flight are noisier which is the reason for the loud buzzing noise normally associated to insects and small birds like the humming bird.

The third type of flyers are bats. Bats are a unique animal because they are the only mammals that is capable of sustained flight. Plus, bats usually flies at a flight regime that is between the flight regimes of a bird and an insect. When compared with both insects and birds, bats have similar flight efficiency as birds since there are several species of bats that do migrate from one place to another, while their glide flights are less efficient than most birds [13] bat flights do not have as high a flapping frequency as insects. Bats however, do dwell indoors particularly in caves which shows that bats have a better maneuver capabilities than birds. It is this mixture of high maneuverability and flight efficiency made bat wings the focus of bio-mimicry for this study. The effects of different flight regimes and the method where a flight regime is measure will be explored later in this study.

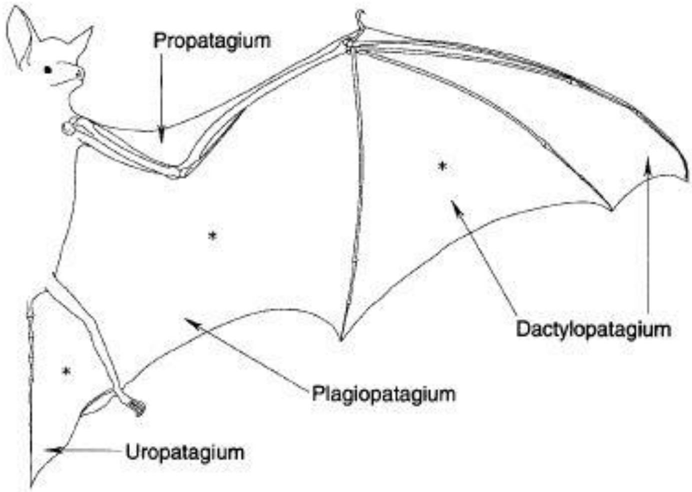


Figure 1: Diagram of a bat wing which have multiple joints that allows for great morph ability of the wing [15]

One of the main factor that allows the bats to have the maneuverability and an efficient flight is due to the anatomy of the bat's wing itself. Unlike insects and most birds, bats have a highly morph-able wing that can not only folds as it flaps by also, since it has a series of flexible tendons that is almost like the human hands (as can be seen in Figure 1) it can change the shape and area of the wing to adapt to any type of flying conditions. One of the method that allows a bat to be maneuverable is, while in flight, a bat will change the camber of its wings in order to turn in specific direction. It is this ability of changing the camber of the wing will be the main focus of this study.

Effects of camber wings on a wing's aerodynamic performance is far from being a new area of study. This is especially true for fixed wings and even fixed wing MAVs. However, a wing's camber effect of a flapping wing is a relatively new area of study [8,9,10,11] and the most relevant findings can be found is a study done by Shkarayev et al. [8]. In that study, it was observed that aerodynamic performance was significantly effected by the wing camber especially when compared to a normal rigid wing. This is the reason why this study aims to investigate the effect of a wing camber on the flight performance especially its effect on the wing's drag. This is important as the drag of the wing will influence the wing's flight but also its maneuverability. Therefore, the main objective for this study is to study the effects of wing camber on a flapping bat inspired wing with flexible skin.

The aerodynamic benefits were evaluated by testing the time average lift generated by the wings with a function of flapping frequency, free stream velocity. The test uses a fixed angle of attack of 10º and uses a flapping mechanism integrated with a novel electronic control system developed in our previous study [7].

Experiment details

Flight conditions

For this study, the flight conditions are described by a non-dimensional parameter named advance ratio (J), which is defined as the ratio of the forward flight speed of the aircraft to the the wingtip velocity of the flapping wing during flight. The advance ratio can be calculated using the following formula;

$$J = \frac{U_\infty}{2fb\theta}$$

Where f is the wing flapping frequency, θ is the total wing flapping angle, and b is the wing span.

Advance ratio will determine the flight regime of the tested flapping wing. If a flapping flight has advance ratio of less than 1, this means that the flapping wing flies at unsteady state flight regime. While if a flapping flight has advance ratio of greater than 1, this means that the flapping wing flies in a quasi-steady state regime. For this study, the flying aerodynamic performance will be tested at advance ratio of 0.2 to 7.0.

The forward flight for the experiment was recreated by blowing a steady free stream air to a stationary model and the air free stream was created by an open test chamber that have a 1ft by 1 ft (0.3 X 0.3 m) open nozzle. The chamber has an air reservoir to ensure the exit air flow is laminar and the air speed was controlled by a digital controller. Diagram for the air camber can be seen in Figure 2. The generated airflow was previously tested using a Laser Doppler Anemometry test and the result shown that the generated free stream has a turbulence rating of 0.3%.

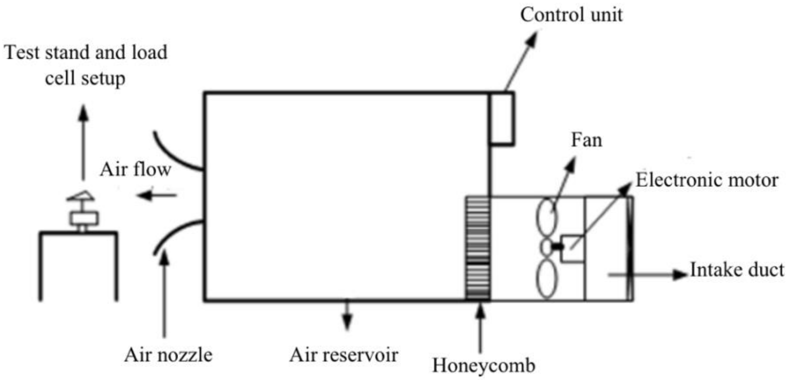


Figure 2: Test chamber and experimental set up diagram

Test Wing

The wing that was tested for this study was the same wing shape that was used in a different previous study done by the author [6]. The wing shape of the tested wing can be seen in Figure 3. All the tested wings have the same chord length (c), wing area (A), and thickness (t). However, the changed variable for the wing design was the camber of the wing. The tested wings camber was 6,9,12, and 15%. The wing camber location with relative of the wing chord can be seen in Figure 4. The tested wings dimensions can be seen in Table 1.

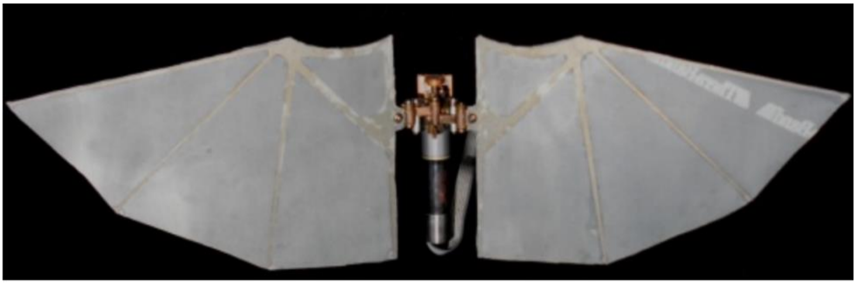
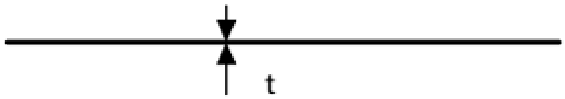
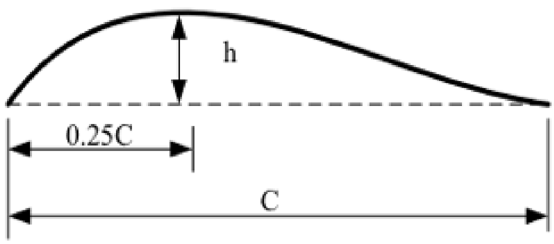


Figure 3: Test wing design shape



(a)



(b)

Figure 4: Side view for the different chamber where; (a) is flat wing and (b) is the cambered wing

Table 1: Test wing dimensions

Camber (%)	6	9	12	15	Flat
Wing area, A (m^2)	0.013	0.013	0.013	0.013	0.013
Chord length, c (mm)	0.08	0.08	0.08	0.08	0.08
Camber height, h (mm)	4.8	7.2	9.6	9.6	-
Thickness, t (mm)	0.35	0.35	0.35	0.35	0.35

Flapping Mechanisms

The flapping motion of the wings was generated using s DC mini motor that was controlled by an Electronic Control System (ECS) that have a in house built Graphical User Interface. The ECS consists of a set of micro-controller, motor driver, an encoder for the DC motor, variable resistor and a power supply. By using this control system, the flapping frequency can be accurately measured and controlled and the error can be reduced from 25-35% to 0.4-1.8%. The flapping motion was also created by a mechanisms system that consists of spokes and gears. Full description for the flapping mechanisms and its control systems was described in a previous work done by the author [7]. This can be seen in Figure 5.

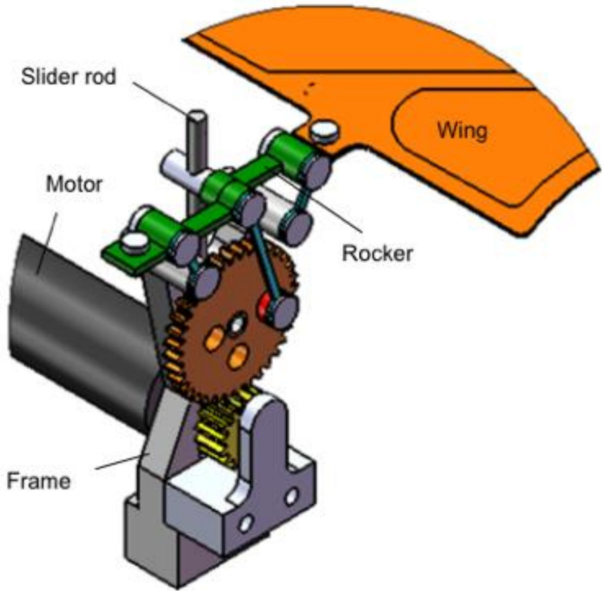
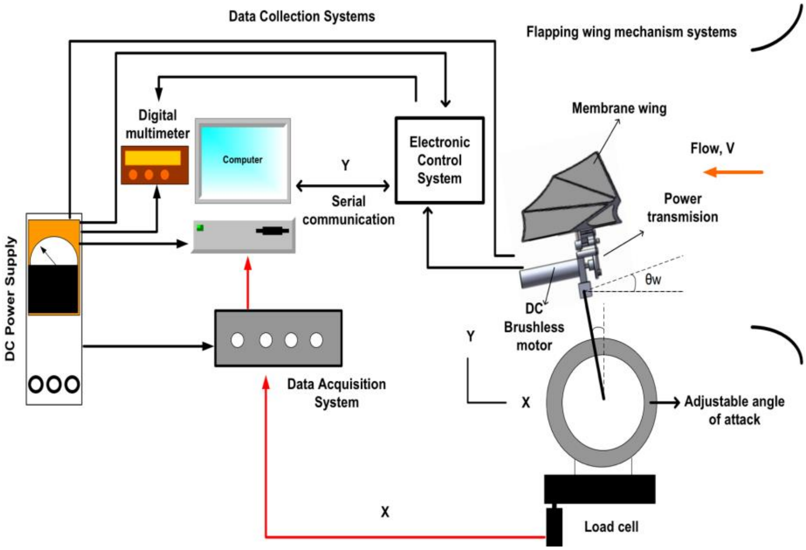


Figure 5: Flapping mechanisms for the flapping wing

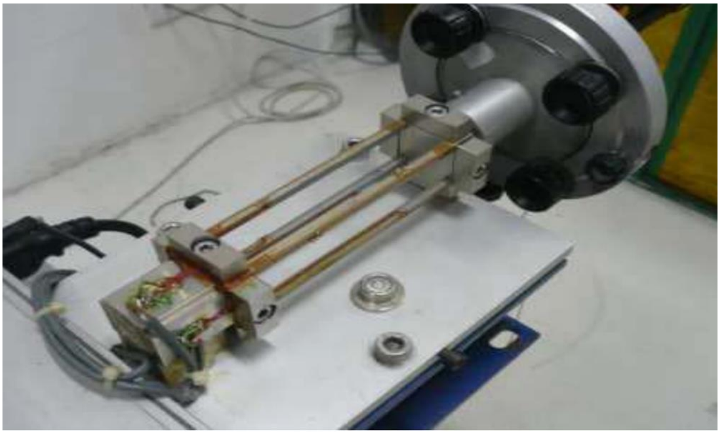
The high precision DELTALAB strain gauge sensor was attached to the flapper system using an intermediate mount, to measure drag. The initial system has been wired and configured to provide measurements for drag. Measurements are based on the displacement of a rigid parallelogram, composed of four beams subjected to bending or torsional loads. Strain gauge is fixed to the beam surfaces. The displacements are very small and the model under test, attached to the balance remains in the same plane, and perpendicular to the flow direction. The precision of the force sensor for measurement in maximum error is 0.3% of the full-scale 5N. The Kyowa data acquisition system (DAQ-type of PCD 300A model) is capable of sampling rates up to 5000 samples per second for each channel input. The calibration of the PCD 300A model was carried out under default channel condition settings having a range of 10000 µm/m, with calibration factor of 1.67 and a zero-offset value (refer figure 1b for set up). LABVIEW 6.0 software provides the necessary user interface for sampling data from the DAQ device and exports the sampled raw data into Microsoft Excel spreadsheet for later aerodynamic analysis. The resolution of the DAQ was 8 bits. Low pass Butterworth filter with cutoff frequency of 5Hz and a second order iterative process was used to smooth the raw data. The experiment data acquisition system set up can be seen in Figure 6. A total of 40,000 data points was collected for every point test condition, which was integrated into time-averaged values drag. The time averaged drag value is then converted into a non-dimensional average drag coefficient or $C_{D\,avg}$. The formula for $C_{D\,avg}$ is shown below.

$$C_{Davg} = \frac{D_{avg}}{0.5\rho U_{\infty}^{2} S}$$

Where D_{avg} is the time averaged lift force, S wing platform area, U_∞ is the forward flight speed and ρ is the air density.



(a)



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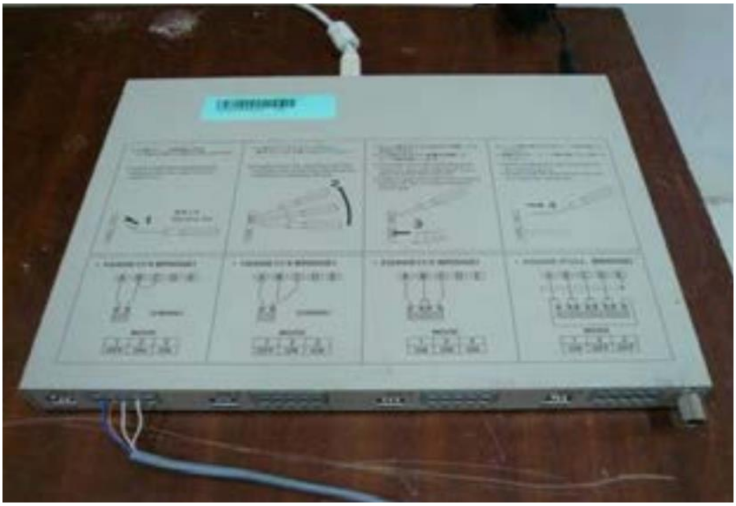

(c)

Figure 6: Data acquisition set up where; (a) is the diagram for the experiment set up, (b) is the load gauge sensor set up, (c) is the Kyowa data acquisition system module

Results and Discussion

The result obtained from the experiment (Figure 7) shown that in a unsteady state flight regime (advance ratio less than 1), the flat wing generated the lowest time averaged drag or $C_{D\ avg}$. This is followed by the 6% camber wing, then followed by the 9% camber wing and followed by the 12% camber wing. The 15% camber wing have the highest $C_{D\ avg}$ value among all the other wings. This shows that the time averaged drag generated increases with increasing wing camber.

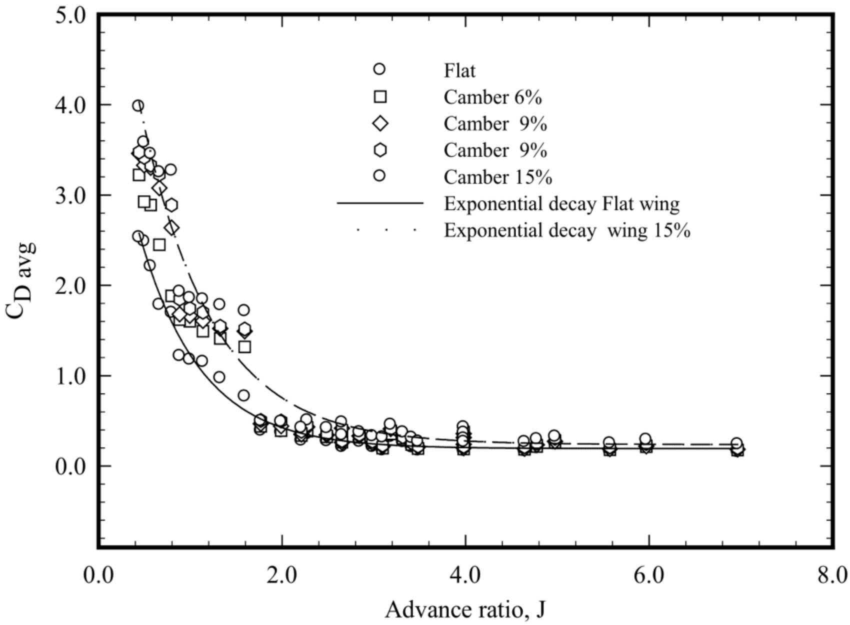

Figure 7: Experimental result for the produced drag at different advance ratio for wings with different wing camber

Since the chord length of the wing is kept constant and the length for the air to travel over the wing is the same for all the different wings, drag due to skin friction does not gives an enough explanation for the difference in generated time averaged drag for the different wings. However, in a previous work done by the author [6], it was observed that with increasing camber will lead to increasing time averaged lift. This finding, offers an explanation to the reason why 6% camber have the lowest generated drag while 15% camber generates the most amount of drag at a quasi-state regime, which is the generated drag for different wing camber is due to the generated induced drag. Where, induced drag means the drag generated as a consequence of the generated lift.

As the advance ratio increases, the C_{davg} decreases for all wing camber, and the rate of decreasing C_{davg} also decreases with increasing advance ratio until a certain point where the C_{davg} remains constant even as the advance ratio increases. Also observed in the collected data, as the advance ratio increases and the test flight enters the quasi-steady state flight, the difference between the C_{davg} for all the wings started to decrease and when the advance ratio reaches 6.0, the C_{davg} for all the wings are close to similar. This shows that the camber of the wing in a flapping wing plays an important role in unsteady state regime flights but as the flight regime enters quasi-steady or steady state flights, the difference between wing camber begins to fade away. It is also important to note that for any of the camber wing, the drag of the wing decreases with increasing advance ratio. Similar pattern is also observed with generated time average lift in the same previous study [6], where as the advance ratio increases the time averaged lift also decreases and the difference between different camber wing also decrease to a point of equal generated lift for all wings. This also suggest that the time averaged drag generated during the study is due to induced drag, which has been found to be a potential problem in a previous work done by G. Sachs [16].

The observed results have shown that wing cambers can affect the produced drag of the flight. From a bio-mimic point of view, this explains why bats are known to varies their wing cambers during flight. Bat operates at a lower advance ratio (unsteady state flight regime) and have a relatively higher flapping `frequency. It has been shown that at this flight regime the wing camber is more important and thus explains why bats capability to varies their wing camber and why their wing skeleton have fingers that extend along the chord length. Birds, especially large birds are more typically dependant on glide flight rather than high frequency flapping and have a relatively higher flight velocity which means that these birds operates at a higher advance ratio and at a quasi-steady flight regime. This explains why varying camber is not as important among birds and why birds wings skeletons does not extend to the chord length and only along the wing span.

From a MAV design point of view, the results show a possible method for controlling the drag of the flight by controlling the wings camber. This is important as having the right amount of drag plays an important role in allowing the MAV to have the maneuverability that is needed to fly in a close and tight areas at a relatively slow speed. Moving forward, the data can be used in figuring out the possible flight flapping mechanisms of a bat inspired MAV.

Conclusions

From the data collected, it was observed that at a unsteady state flight regime (advance ratio less than 1), the C_{davg} increases with increasing camber. However, as the advance ratio increases, the C_{davg} decreases and the the difference in C_{davg} among different wing camber also decreases until a certain point where the C_{davg} is constant and the C_{davg} of all wing camber has converged and equals in value. The changed in C_{davg} is due to the generated lift. The data also shows that wing camber have an effect on the C_{davg} during a low advance ratio flight but the effect decreases with increasing advance ratio.

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