Helicopter blade tracking by laser light

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A new helicopter rotor blade tracking method based on the diffuse reflection of laser light is presented. The blade tip paths are marked by bright flashes of laser light reflected on the running blades. The flashes are detected by a television camera and after appropriate digital processing displayed on a tv monitor. The method offers an exceptional accuracy of about 1 mm and very good reproducibility.

KEYWORDS: lasers, helicopter blade tracking

Introduction

A common cause of vibration in helicopters is an out-of-track rotor. Rotor blades are in-track when the tip paths of all the blades coincide (Fig. 1). When out-of-track a rotor requires 'tracking', which means finding out which blade or blades are riding high or low, and applying the corrective action according to the particular type of helicopter (the actual trimming and balancing are beyond the scope of this paper). Helicopter tracking can be accomplished in many ways. The simplest methods are mechanical ones like tracking by brush or flag.

With the so-called brush method an oil-soaked brush with a long handle is brought towards the rotor tips from underneath. The brush touches the lowermost blade(s) which, when stopped, is revealed by the oil mark. In the more elaborate flag method, the blade tips are marked with different coloured chalks. The rotor is rotated at normal speed and a canvas or paper flag is brought towards the blades until the tips are touched and chalk marks are left on the flag. The chalk marks reveal the respective tip paths of the blades and show the amount of alteration required to bring them into track.

The more advanced optical methods have the main advantages over mechanical ones of not interfering with the blades, greater accuracy and safe operation. For the so-called mirror method, coloured mirrors (for example, cats-eyes) are fitted under the blade tips. With the blades rotating, a lamp of considerable power is shone at the tips and their relative positions can be seen. Another version takes advantage of the stroboscopic effect. A flash-lamp is held by an operator in the cockpit and aimed at the underside of the rotor blade tips. The rotating blades periodically intercept the laser beam and a certain part of the diffusely reflected energy is picked up by the tv camera. The video output of the camera is fed into the processor, which determines the vertical deviations of the blade tip paths and displays the result on a tv monitor. For this purpose, the processor receives identifying pulses from the counter detecting the laser flashes from below. From this position all the flashes seem to occur in the same direction, that is, along the laser beam. Therefore, apart from some blurring

The suggested system

We shall now outline a simple optical tracking method based on the diffuse reflection of laser light. Taking into consideration the very small divergence of the laser beam, the mirror method seems to be disadvantageous because the reflected beam cannot be seen beyond a rather narrow sector. This makes it practically impossible to track the blades of a vibrating helicopter which inevitably moves slightly. On the other hand, the laser-illuminated spot on a diffusely reflecting blade tip seems to be of the same brightness independent of the direction of observation, although it must also be taken into consideration that the light energy received by the optical detector is inevitably very low.

The schematic of the suggested system and its practical realization are shown in Figs 2a and b respectively. A narrow monochromatic laser beam is aimed at the underside of the rotor blade tips. The rotating blades periodically intercept the laser beam and a certain part of the diffusely reflected energy is picked up by the tv camera. The video output of the camera is fed into the processor, which determines the vertical deviations of the blade tip paths and displays the result on a tv monitor. For this purpose, the processor receives identifying pulses from the counter detecting the laser flashes from below. From this position all the flashes seem to occur in the same direction, that is, along the laser beam. Therefore, apart from some blurring
Loser flashes

Rotor:
Laser beam

"r"

Laser and counter

Televwon camera

Identification pulses

Processor with television monitor

Video signal

The processor displays the vertical positions of the flashes on the monitor by bright rectangles, laterally shifted according to the serial number of the appropriate blades (Fig. 3). The vertical positions of the rectangles refer to the last appropriate flashes, that is, the processor eliminates the disturbing flickering associated with conventional optical tracking methods. Bright raster lines make the evaluation more accurate. The processor has two additional filtering functions which are necessary for increasing the reproducibility of the tracking.

The vertical coordinates of the laser flashes are rather uncertain due to a relatively slow common-mode swinging and a faster differential-mode vibration. The former component is mainly caused by the irregular precession of the rotor brought about by abrupt gusts of wind and partly by the pilot changing the rotor angle to balance against the alternating wind pressure. Significant common-mode swinging can also be experienced due to slight changes in revolution speed; the blades exhibit astonishing elasticity and are raised by the centrifugal force such that a few percent change in speed can result in considerable elevation or fall of the blade tips.

The fairly slow common-mode swinging is effectively rejected by the processor determining the vertical coordinates of the flashes related to the last position of the reference blade-tip. In this case, the first rectangle modelling the reference blade is fixed to the central raster line on the TV screen and only the relative positions of the other blades are displayed. Of course, these relative coordinates are changing irregularly to a certain degree, due to the independent vibration of the blades and the inadequate common-mode swinging rejection.

In the case of too fast a common-mode swinging, the vertical coordinate of the reference blade changes considerably during one revolution of the rotor, which results in the quasi-random scattering of the relative coordinates of the other blades. This kind of error can be effectively eliminated by the processor averaging the measured relative coordinates for a few periods. In the real-time mode the rectangles on the monitor always refer to the vertical positions of the last appropriate flashes, which badly limits the accuracy and reproducibility of the tracking. In the averaging mode these specifications are greatly improved and can achieve an accuracy of about 1 mm.

Optical threshold sensitivity

The above-mentioned advantageous properties and excellent measuring parameters of the suggested system are due to
the diffuse reflection of the laser light. However, this also brings about a rather serious problem: only a very small fraction of the total laser light gets into the camera objective. In spite of this, the absolute detectability of the laser flashes remains satisfactory because of the very high sensitivity of the available special pick-up tubes, such as chalnicon or silicon target vidicons. On the other hand, the background brightness of the sky can achieve a peak luminance as high as 15-30 000 cd m\(^{-2}\), which badly limits the relative detectability of the rather short laser flashes.

In the following we shall try to estimate the optical threshold sensitivity of the suggested system, that is, the highest background luminance at which the laser flashes are reliably detectable in the video signal of a well focused camera.

The rotor blade tips are illuminated by a narrow laser beam of Gaussian intensity distribution

\[ I(r) = I_0 e^{-r^2/d_0^2} \]

(1)

where \(I_0\), \(r\) and \(d_0\) denote the peak intensity of the laser beam in the centre of the illuminated spot, the radius from the beam axis and the \(1/e^2\) diameter of the impinging beam respectively. The so-defined diameter is given by

\[ d_0 \approx h \varphi \]

(2)

where \(h\) is the distance from the laser to the blade tips and \(\varphi\) is the divergence of the laser beam.

According to our experiments, a contrast ratio of two can be easily detected in the video signal of the camera, therefore in our special case it seems to be more reasonable to use the \(-3\) dB diameter \(d_1\) instead of \(d_0\). From (1) and (2)

\[ d_1 \approx 0.6 h \varphi \]

(3)

From (1) it can be calculated that only 50\% of the total laser energy falls into the central part of the illuminated spot of diameter \(d_1\) (it is about 86\% in the case of the more widely used \(d_0\)). The average intensity of this central part of the laser beam is given by

\[ I_{sp} \approx 1.8 \frac{P_1}{h^2 \varphi^2} \]

(4)

where \(P_1\) denotes the total laser power. The average luminance of the so-defined spot can be determined according to the Lambert law

\[ B_{sp} = \frac{R I_{sp}}{\pi} \]

(5)

where \(R\) is the reflection coefficient of the blade-tip surface. In case of sufficiently clean, white blade-tips, \(R\) is about 0.6.

The above equations can be used to estimate the average luminance of the laser spot appearing on the standing blades. Let us choose a 10 mW HeNe laser with a beam divergence of 1.2 mrad. Assuming a 4 m distance between the laser and the running blades, the diameter of the illuminated spot is about 3 mm and the radiometric brightness is about 150 W m\(^{-2}\) sr\(^{-1}\). Taking into consideration that the relative visibility function at 632.8 nm is about 0.25, the luminous brightness will be about 25 000 cd m\(^{-2}\).

Of course, the system must be placed so that direct sunlight cannot get into the camera. The peak luminance of the blue sky in the background seems to be about 3000 cd m\(^{-2}\), but white clouds of about ten times higher luminance may occur under unfavourable light conditions.

We can conclude that the monochromatic laser spot on a standing or slowly-moving blade is easily visible to the naked eye, so the system can be set up properly without any difficulty. During the actual tracking with the rotor rotating, the effective brightness of the laser flashes will be much less than that of the laser spot on a standing blade:

\[ B_{sp\ eff} = n_{eff} B_{sp} \]

(6)

where \(n_{eff}\) denotes the effective duty factor of the pulse-train. The duration of the laser flash \(t_d\) and its repetition time \(t_p\) depend on the particular type of helicopter to be tracked. Let us assume that the tips of 6 m long and 15 cm wide blades are running at a normal speed of 200 m s\(^{-1}\), so \(t_d\) and \(t_p\) are about 0.75 ms and 190 ms respectively. The duty factor of the laser flashes received by the camera is

\[ \eta = \frac{t_d}{t_p} \approx 0.004 \]

(7)

Using a camera of very long integrating time, \(\eta\) is equal to the effective duty factor. The integrating time of the camera mainly depends on the lag time of the photosensitive material used in the pick-up tube and the frame-time of the scanning system. It is easy to see that the effective duty factor can be greatly increased by using a pick-up tube of minimal lag time; for instance, about 20 ms can be achieved by silicon-target vidicons. At the same time the frame frequency must be increased to take full advantage of the reduced lag time, and it seems to be advisable to alter the conventional interface scanning system into a direct one. By these simple electronic modifications the effective duty factor can be increased to about 0.04 for a silicon-target vidicon camera.

In spite of this, the effective brightness of the laser flashes will be considerably lower than the background luminance. Therefore a narrow-band interference filter must be applied in front of the pick-up tube to discriminate the monochromatic laser flashes against the scattered white-light of the sky. The bandwidth of the visibility function formerly used in our calculations is about 120 nm, and its value at 632.8 nm is about 0.25. Using a 3 nm interference filter an improvement in signal-to-background ratio of about 160 can be achieved, which amply compensates the rather low duty factor of the flash-train.

A contrast ratio of two must be ensured to detect the laser flashes safely, that is, the effective brightness of the rather short flashes should be at least equal to the background luminance. Therefore if the signal-to-background ratio to be about six times higher than the necessary unit value, the detection might be hindered by practical problems formerly neglected. First, the useful signal can be considerably reduced by blurring due to the inevitable focusing error caused by seeking the flashes with a camera of rather low angle-of-view. Therefore, the lateral aiming at least must be accomplished with standing blades, which also results in an approximate focusing. The effective duty factor of the laser flashes can be further reduced by vertical blurring of the illuminated spot due to the particular shape of the blades and/or the angle between the blade planes and
the horizontal. For instance, if this angle is 5° the vertical diameter of the reflected spot will be increased to about five times its horizontal value, which results in the decreasing of the effective brightness by about the same factor.

Conclusions

The suggested tracking method offers an exceptional accuracy of about 1 mm which can be further increased by using a focusing telescope to reduce the diameter of the laser illuminated spot on the blades, and increasing the optical magnification of the camera objective. To take full advantage of this high accuracy, special measures must be taken to reject the extraneous disturbing factors such as swings and vibrations, which limit the reproducibility of the tracking. This problem can be easily solved by a digital processor integrating the relative deflections between the blade-tip paths.

The threshold sensitivity of the suggested system is approximately equal to the highest background luminance to be expected, but a further improvement in signal-to-background ratio would have a beneficial effect on its operation. According to our experiments, a signal-to-background ratio at least four times higher should be ensured to reliably detect the laser flashes when aiming with the inevitably slightly out-of-focus camera.

Searching for the flashes might become a rather serious problem when tracking helicopter blades of lower effective duty factor or reflection coefficient, and therefore further development is needed to increase the signal-to-background ratio. It seems to be rather expensive to increase the laser power or the selectivity of the interference colour filter, but the effective duty factor of the laser flashes might be further increased by using special high speed cameras or conventional ones with electro-optical shutters.

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