Common-mode noise rejection using fringe-locking method in WEP test by simultaneous dual-species atom interferometers*

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We theoretically investigate the application of the fringe-locking method (FLM) in the dual-species quantum test of the weak equivalence principle (WEP). With the FLM, the measurement is performed invariably at the midfringe, and the extraction of the phase shift for atom interferometers is linearized. For the simultaneous interferometers, this linearization enables a good common-mode rejection of vibration noise, which is usually the main limit for high precision WEP tests of the dual-species kind. We note that this method also allows for an unbiased determination of the gravity accelerations difference, which meanwhile is ready to be implemented.

Keywords: weak equivalence principle, dual-species atom interferometers, fringe locking, vibration noise rejection

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1. Introduction

Benefitting from the highly developed atom interferometry technology, cold atoms, possessing both internal and external degrees of freedom, become ideal probes in many precision measurements. They have been successfully used in measuring gravity acceleration,[1–10] gravity gradient,[7,8,11–16] rotation,[17–23] magnetic field gradient,[24–27] etc. Atom interferometers also play an important role in fundamental physics, such as the measurement of fine structure constant, the determination of gravitational constant G,[28–30] and the test of the weak equivalence principle (WEP).[2,10,31–37]

The weak equivalence principle, as one of the cornerstones of Einstein's general relativity, states that all masses fall in the same way in a gravitational field regardless of their internal structure and composition. Verifications of WEP using macroscopic masses have achieved a level of 10^{-13},[38,39] while the best level for testing WEP on quantum basis is at the level of 10^{-9}.[2,10] Testing WEP using microscopic particles still stimulated wide interest since the development of the neutron interferometer.[40] The advantage of quantum-basis tests is that, quantum objects offer more possibilities to break WEP and meanwhile they also afford potentially higher precision and well defined properties.[34,41,42] Up to now, WEP tests on quantum basis have been performed between atoms and macroscopic bodies,[2,10] between atoms of different species,[34] and different permutation symmetries, e.g., bosons and fermions,[35] as well as the same atoms of different hyperfine levels,[31] or in different spin orientations.[37] In these tests, the corresponding gravity accelerations of different objects are usually independently measured and then compared, in which situation the vibration noise cannot be common-mode rejected. To overcome this difficulty, WEP test using simultaneous dual-species atom interferometers is of particular interest for its intrinsic capability of the common-mode vibration noise rejection (CMVNR).[32,36] WEP tests of this kind have already been performed by several groups, achieving a level of 10^{-8},[36] and tests with higher precision have been proposed,[43,44] or even under development.[45,46]

However, CMVNR in WEP tests of dual-species kind, especially using non-isotope species, is not so direct as that, in atom gradiometers. In the latter case, it is well developed to extract the differential phase shift $\Delta\Phi$ in a common-mode noises immune way by the ellipse fit method[47] or Bayesian estimation.[48–50] In WEP tests of dual-species kind, however, the scale factors $S_j \cong k_j^{\text{eff}} T_j^2$ are usually different for the two interferometers. The difference originates from the different effective Raman wave vectors used for the atom species $j = 1$ and 2 when the pulses separation times T_j are the same. The different scale factors cause two aspects of complexity in the signal extraction of WEP tests. Firstly, the interested signal $\Delta g \equiv g_1 - g_2$ is not proportional to the differential phase shift, which excludes the direct extraction of Δg using the usual ellipse fit method or Bayesian estimation. Secondly, the induced phase fluctuations by vibration noise are also different for the two interferometers, which increases the difficulty to

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the CMVNR. The scale factors can be made the same by using different pulses separation times T_j, which is particularly favorable in the case of the ratio $r \equiv k_2^{\rm eff}/k_1^{\rm eff}$ close to unity.[49] However, in this situation, the vibration noise is not exactly the same as experienced by the two interferometers, which thus excludes the possibility of perfect common-mode rejection. Alternatively, it is proposed to simultaneously measure the vibration noise by an auxiliary sensor and then reconstruct the fringes.[51,52] The effectiveness of this method depends on the quality of the correlation between real and measured vibrations, which is hard to ensure when the aimed precision of the WEP test is beyond the intrinsic noise of state-of-the-art vibrations sensors. This problem may also be mathematically resolved by an improved ellipse fit method, Bayesian estimation or direct phase extraction.[33,50,52] However, these solutions either require complex computation (sometimes even causing a bias result) or suffer from the trouble of separating the WEP violation signal from total differential phase shift.

It is already clear that the gravity acceleration or the vibration induced phase shift is linear to $k_j^{\rm eff}$, and we further note it is the conventional non-linear phase extraction process from the interference fringe that complicates the WEP violation signal separation and the CMVNR. Actually, the fringe-locking method (FLM) has already been adopted formerly for single interferometers[53–56] and recently for coupled interferometers,[16] by which the signal extraction of the interferometer can be linearized. In this work, we propose to operate the dual-species atom interferometers in the fringe-locking manner to linearize the signal extraction, which promises a good CMVNR, especially in the case of low level vibration noise. We note that, in the WEP test of dual-species kind, it only needs a change in the control of the Raman lasers effective frequencies to perform the FLM, and the corresponding signal extraction is direct. Moreover, this FLM allows for an unbiased determination of Δg.

2. Review of fringe-locking method

In light pulses atom interferometers, the interference pattern is usually manifested as the variation of the transition probability between the two ground levels of the atom. The transition probability P is typically expressed as[1,3]

$$P = A + B\cos(\varphi + \varphi_{\rm m}), \tag{1}$$

which forms a cosine fringe when the controllable φ is scanned. In Eq. (1), A is the fringe offset, B is the fringe amplitude, and $\varphi_{\rm m}$ indicates the phase shift induced by the physical quantity to be measured. In the conventional method, a full cosine fringe is obtained by scanning φ step by step, as shown in Fig. 1(a), and $\varphi_{\rm m}$ is then acquired by a cosine fitting. Alternatively, the FLM can be adopted,[53–55] as shown in Fig. 1(b). In the FLM, the appropriate value of φ, denoted as φ^0, is found to make $\varphi + \varphi_{\rm m} \sim 2n\pi$ (where n is an integer). Then φ is modulated by $\pm\pi/2$ respect to the center of φ^0 so that the measurement is always performed at the midfringe, alternately to the right and to the left side of the central fringe. In this case, the transition probabilities P for every two consecutive launches can be expressed as

$$P[2l-1] = A + B\cos(\varphi^0 + \varphi_{\rm m} - \pi/2), \tag{2a}$$

$$P[2l] = A + B\cos(\varphi^0 + \varphi_{\rm m} + \pi/2), \tag{2b}$$

where l ($l = 1,2,3,\ldots$) denotes the index of modulating cycles. The difference between $P[2l-1]$ and $P[2l]$ could be used as a criterion of whether $\varphi^0 + \varphi_{\rm m} = 2n\pi$ is fulfilled, which in turn enables feedback control of φ^0. According to the linear approximation of Eqs. (2a) and (2b) at the midfringe, the correction can be expressed as

$$\delta(\varphi^0) = (P[2l] - P[2l-1])/2B, \tag{3}$$

where the fringe amplitude B must be known in advance by scanning the full fringe. Once the corrections are made to form a closed feedback loop, the equation $\varphi^0 + \varphi_{\rm m} = 2n\pi$ is supposed to be reached, from which the value of the interested $\varphi_{\rm m}$ can be deduced from φ^0 in a linear way. It is shown in Eq. (3) that when the interferometer is operated at the midfringe, the measurement works in a linear region. This linearization character is helpful for signal extraction in the WEP test of dual-species kind, as will be discussed in detail in the following section.

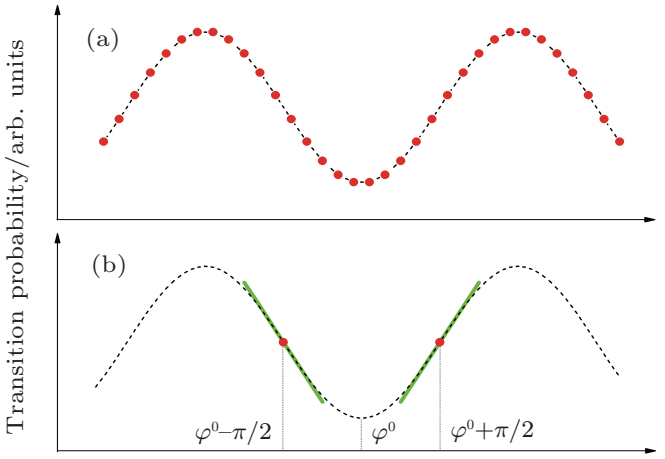


Fig. 1. (color online) Different methods to operate the interferometer, with (a) for recording full fringes and (b) for performing measurements at the midfringe. In the conventional method, the phase is scanned step by step, while in the FLM, the phase is modulated by $\pm\pi/2$ with respect to an appropriate center, denoted as φ^0 here. The dash lines are given here to guide the eyes. The two thick green lines are the tangent lines of the midfringe, which show good approximation for the fringe near the center.

3. Application in WEP test

In the above section, the FLM for single interferometer is illuminated, and the Raman laser phase is convenient to con-

trol, which thus usually plays the role of φ. Generally speaking, one needs two independent controllable phases to simultaneously lock two interferometers. In Ref. [16], in addition to the Raman laser phase, the phase shift due to the magnetic field gradient is explored as the other controllable phase for an atom gravity gradiometer. In a WEP test using simultaneous dual-species atom interferometers, there are already two independent groups of Raman lasers (usually one group used for one species atom), and thus it is natural to explore the two controllable Raman laser phases for fringe locking.

For each species atom interferometer using $\pi/2-\pi-\pi/2$ Raman pulses scheme, the controllable phase φ, namely the Raman lasers phase, can be expressed as[33,50,52,57]

$$\varphi_j=\alpha_j(T_j+2\tau_j)(T_j+4\tau_j/\pi)\equiv\alpha_j f_{\rm DC}(T_j,\tau_j), \tag{4}$$

where α_j is the chirp rate of the effective Raman laser frequency used to compensate the Doppler shift due to gravity, and τ_j is the $\pi/2$ pulse duration. With the Raman pulses duration effect neglected, $f_{\rm DC}(T_j,\tau_j)$ just simplifies to T_j^2. The interested phase $\varphi_{\rm m}$, namely the phase related to the gravity acceleration, can be expressed as[33,50,52,57]

$$(\varphi_{\rm m})_j=k_j^{\rm eff}g_j f_{\rm DC}(T_j,\tau_j), \tag{5}$$

where the gravity acceleration of j species atoms is denoted as g_j to account for possible WEP violation. In order to clearly manifest the ability of common-mode rejection with FLM, the phase due to vibration is explicitly included in the total phase shift, which can be expressed as[33,50,52,57]

$$\begin{aligned}(\varphi_{\rm vib})_j&=k_j^{\rm eff}\int_{-\infty}^{\infty}\xi(t-(t_i)_j)\int_{-\infty}^{t}a(t')\,{\rm d}t'\,{\rm d}t\\&\equiv k_j^{\rm eff}h(T_j,\tau_j;a(t),(t_i)_j),\end{aligned} \tag{6}$$

where $\xi(t)$ is the sensitivity function,[58] and t_i is the central time of the interfering progress for the ith shot measurement. We note that both $f_{\rm DC}(T_j,\tau_j)$ and $h(T_j,\tau_j;a(t),t_i)$ are irrelative to $k_j^{\rm eff}$.[33,50,52,57] In the case of identical pulses separation time (namely $T_1=T_2\equiv T$), identical effective Rabi frequencies (thus $\tau_1=\tau_2\equiv\tau$), and simultaneous interferometers (thus $(t_i)_1=(t_i)_2\equiv t_i$ as well as experiencing the same vibration noise $a(t)$), $f_{\rm DC}(T_j,\tau_j)$ and $h(T_j,\tau_j;a(t),t_i)$ are identical for the dual-species atom interferometers. This is exactly the situation we hope (and also are able to) manage to achieve, we then abbreviate $f_{\rm DC}(T,\tau)$ and $h(T,\tau;a(t),t_i)$ as $f_{\rm DC}$ and $h[i]$, respectively.

Once the appropriate values of Raman laser phase, denoted as φ_j^0, are found to make $\varphi_j+(\varphi_{\rm m})_j\sim 2n_j\pi$ for each of the interferometers, the Raman laser phases are then modulated by $\pm\pi/2$. The corresponding transition probabilities for the two interferometers for every two consecutive launches can be expressed as

$$\begin{aligned}P_j[2l-1]=A_j+B_j\cos(&\varphi_j^0+k_j^{\rm eff}g_j f_{\rm DC}\\&+k_j^{\rm eff}h[2l-1]-\pi/2),\end{aligned} \tag{7a}$$

$$\begin{aligned}P_j[2l]=A_j+B_j\cos(&\varphi_j^0+k_j^{\rm eff}g_j f_{\rm DC}\\&+k_j^{\rm eff}h[2l]+\pi/2).\end{aligned} \tag{7b}$$

In the same way as in a single interferometer, the correction is made as

$$\delta((\varphi_j^0)[l])=(P_j[2l]-P_j[2l-1])/2B_j, \tag{8}$$

where l denotes the lth correction (the index of φ_j^0 is explicitly indicated here). The $(l+1)$-th phase modulation center will be $(\varphi_j^0)[l+1]=(\varphi_j^0)[l]+\delta((\varphi_j^0)[l])$. For a single interferometer, the l-th measured value of the gravity acceleration is then expressed as

$$(g_{\rm meas})_j[l]=(2n_j\pi-\varphi_j^0[l]-\delta((\varphi_j^0)[l]))/k_j^{\rm eff}f_{\rm DC}.$$

This measured value is obviously affected by the vibration noise, which can be actually explicitly deduced from the linear approximation of Eqs. (7a) and (7b) at the midfringe, namely

$$(g_{\rm meas})_j[l]=g_j+(h[2l-1]+h[2l])/2f_{\rm DC}. \tag{9}$$

However, the measured WEP violation signal is the difference of the measured gravity accelerations, which is then expressed as

$$(\Delta g)_{\rm meas}[l]\equiv(g_{\rm meas})_1[l]-(g_{\rm meas})_2[l]=g_1-g_2, \tag{10}$$

which is exactly the possible WEP violation signal one searches for. It is clearly shown from Eq. (10) that the FLM promises a perfect CMNVR within the first order approximation for WEP tests using simultaneous dual-species atom interferometers. This common-mode rejection capability profits from the linearized signal extraction.

4. Simulation and result

Equation (9) is based on the linear approximation of the measurement equations (7a) and (7b), and so is the consequent common-mode rejection. Actually, vibration noise would cause a departure of the measurement point from the midfringe, which would then affect the linear approximation. It is easily imagined that this affection will increase with the noise level. Since the vibration noise induced phases for the two interferometers are different, the relative sites of the measurement points at the respective fringe are also different, which will limit the common-mode rejection capability of this fringe-locking method. The rejection capability will be investigated here by numerical simulation. For simplicity, in the simulation the transition probabilities are re-written as

$$P_1=A_1+B_1\cos(\varphi_1+(\varphi_g)_1+\varphi_{\rm vib}), \tag{11a}$$

$$P_2 = A_2 + B_2\cos(\varphi_2 + r(\varphi_g)_2 + r\varphi_{\rm vib}), \qquad (11b)$$

where $(\varphi_g)_1$ is equivalent to $(\varphi_{\rm m})_1$, and $(\varphi_g)_2$ is defined as $(\varphi_g)_2 \equiv k_1^{\rm eff} g_2 f_{\rm DC}$. With this redefinition, $(\varphi_g)_1 = (\varphi_g)_2$ in the absence of WEP violation. The vibration noise is simulated by randomly drawing the values of $\varphi_{\rm vib}$ in a Gaussian distribution with a standard deviation of $\sigma_{\varphi_{\rm vib}}$. To simulate the fringe locking, the Raman laser phase φ_1 (φ_2) is modulated by $\pm\pi/2$ with a center of φ_1^0 (φ_2^0), and the corrections for every two consecutive launches are made as Eq. (8) (the initial values of φ_1 and φ_2 are $-(\varphi_g)_1$ and $-r(\varphi_g)_2$, respectively). The corresponding measured phase shifts due to gravity acceleration are then $(\varphi_g)_1^{\rm meas} = -\varphi_1^0$ and $(\varphi_g)_2^{\rm meas} = -\varphi_2^0/r$, respectively, from which the interested possible WEP violation signal can be deduced as $\Delta\Phi_g \equiv (\varphi_g)_1 - (\varphi_g)_2 = -(\varphi_1^0 - \varphi_2^0/r)$.

In the numerical simulation, the dependence of the common-mode rejection efficiency on the vibration noise level (characterized by $\sigma_{\varphi_{\rm vib}}$) and the ratio of the effective Raman wave vector (characterized by r) is investigated. For each $\sigma_{\varphi_{\rm vib}}$ and r, 10^4 modulation cycles are simulated for the two interferometers, in which process 2×10^4 pairs (P_1, P_2) are generated with $A_1 = A_2 = 0.5$ and $B_1 = B_2 = 0.5$ and 10^4 pairs $((\varphi_g)_1^{\rm meas}, (\varphi_g)_2^{\rm meas})$ are obtained. The influence of the vibration noise on the interested signal is characterized by the Allan deviation of the $\Delta\Phi_g$, which is calculated by the obtained pairs $((\varphi_g)_1^{\rm meas}, (\varphi_g)_2^{\rm meas})$. Since the simulated vibration noise is white noise, the calculated Allan deviation of $\Delta\Phi_g$, denoted as $\sigma_{\Delta\Phi_g}(N)$, scales down by the inverse square-root of the number of measurement, namely $\sigma_{\Delta\Phi_g}(N) = \sigma^1_{\Delta\Phi_g}/\sqrt{N}$. Here N denotes the number of measurements, and $\sigma^1_{\Delta\Phi_g}$ stands for the measurement sensitivity, which is obtained by white noise model fitting of $\sigma_{\Delta\Phi_g}(N)$ versus N.

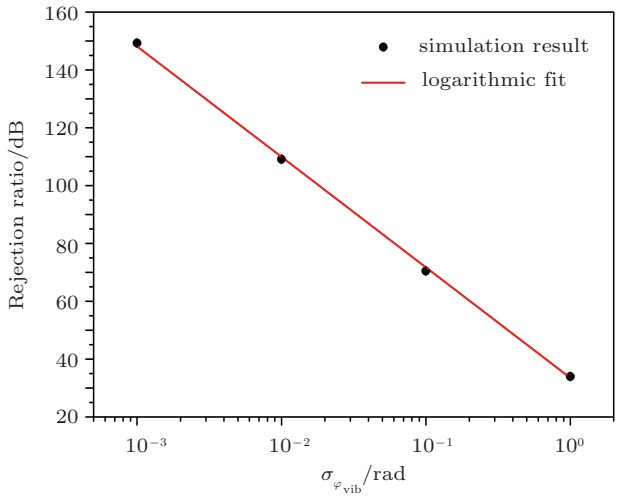


Fig. 2. (color online) Variation of the rejection ratio along the vibration noise level. In this group of simulations, the gravity induced phase is set as $(\varphi_g)_1 = (\varphi_g)_2 = 2$ rad, and the ratio for the effective Raman wave vector is set as 780/767, the value for the dual-species of ^{39}K versus ^{87}Rb.

The efficiency of the common-mode noise rejection is characterized by the rejection ratio $\sigma_{\varphi_{\rm vib}}/\sigma^1_{\Delta\Phi_g}$. The simulation result for the dependence of the rejection ratio on the vibration noise level $\sigma_{\varphi_{\rm vib}}$ is shown in Fig. 2. According to the logarithmic fit in Fig. 2, the rejection ratio scales by $-38.2(1)$ dB per octave, which is very close to the expected value of -40 dB per octave as a result of the third order expansion of the sinusoid function. This means that the CMVNR capability of the FLM improves quite fast as the vibration noise decreases. This simulation also indicates that even if the vibration noise is as large as 1 rad, there is still about 33 dB rejection ratio for the ^{39}K versus ^{87}Rb dual-species interferometers.

The simulation for different r is then performed with a fixed vibration noise level of $\sigma_{\varphi_{\rm vib}} = 1$ mrad. The result is shown in Fig. 3, which also shows a logarithmic relation. According to the logarithmic fit, the rejection ratio scales down by $-19.98(4)$ dB per octave. It is shown that even if the deviation of the ratio from unity is as large as 1, there is still about 110 dB rejection ratio for $\sigma_{\varphi_{\rm vib}} = 1$ mrad.

In addition to the CMVNR capability, the bias of the extracted $\Delta\Phi_g$ is also highly important. We have checked that the average value of $\Delta\Phi_g$ extracted by this fringe-locking method is exactly equal to the differential value of the set $(\varphi_g)_1$ and $(\varphi_g)_2$, whatever the vibration noise level (as long as $\sigma_{\varphi_{\rm vib}} \le 1$ rad) and the ratio of the effective Raman wave vector are.

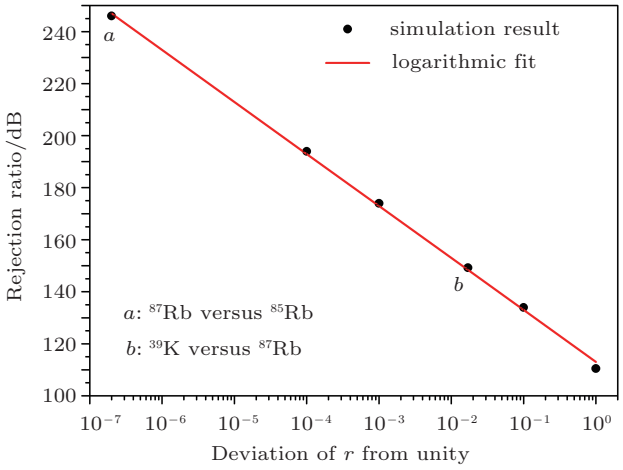


Fig. 3. (color online) Dependence of the rejection ratio on the ratio of the effective Raman wave vector. The ratios for dual-species of ^{87}Rb versus ^{85}Rb and ^{39}K versus ^{87}Rb are explicitly displayed. In this group of simulations, the gravity induced phase is set as $(\varphi_g)_1 = (\varphi_g)_2 = 2$ rad, and the vibration noise level is fixed at $\sigma_{\varphi_{\rm vib}} = 1$ mrad.

5. Discussion and conclusion

The simulation for different fringe amplitudes of the two interferometers (namely $B_1 \neq B_2$) is also performed, and the dependence of the rejection ratio on $\sigma_{\varphi_{\rm vib}}$ and r does not change. This is consistent with our knowledge. In the presence of phase noises only, the absolute value of the amplitude does not matter much for the FLM as long as it is known exactly. In an actual experiment, the fringe amplitudes of the two interferometers are pre-determined by scanning the full fringe and

then performing cosine fittings. In the fringe-locking mode, the realtime information about the fringe amplitudes is lost, of which possible drift will affect the fringe-locking. This can be resolved by occasionally switching back to the full-fringe recording mode to get renewed fringe amplitudes.

In conclusion, we have shown the capability of CMNVR using FLM in WEP test by simultaneous dual-species atom interferometers. We note that it is convenient to perform this method in the dual-species interferometers, and it is also direct to extract the signal. Of importance, this signal extraction approach allows for an unbiased determination of the gravity accelerations difference, and allows a good common-mode noise rejection, especially in the low vibration noise level. This will thus alleviate the demand for the vibration noise isolation in WEP test of the dual-species kind.

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