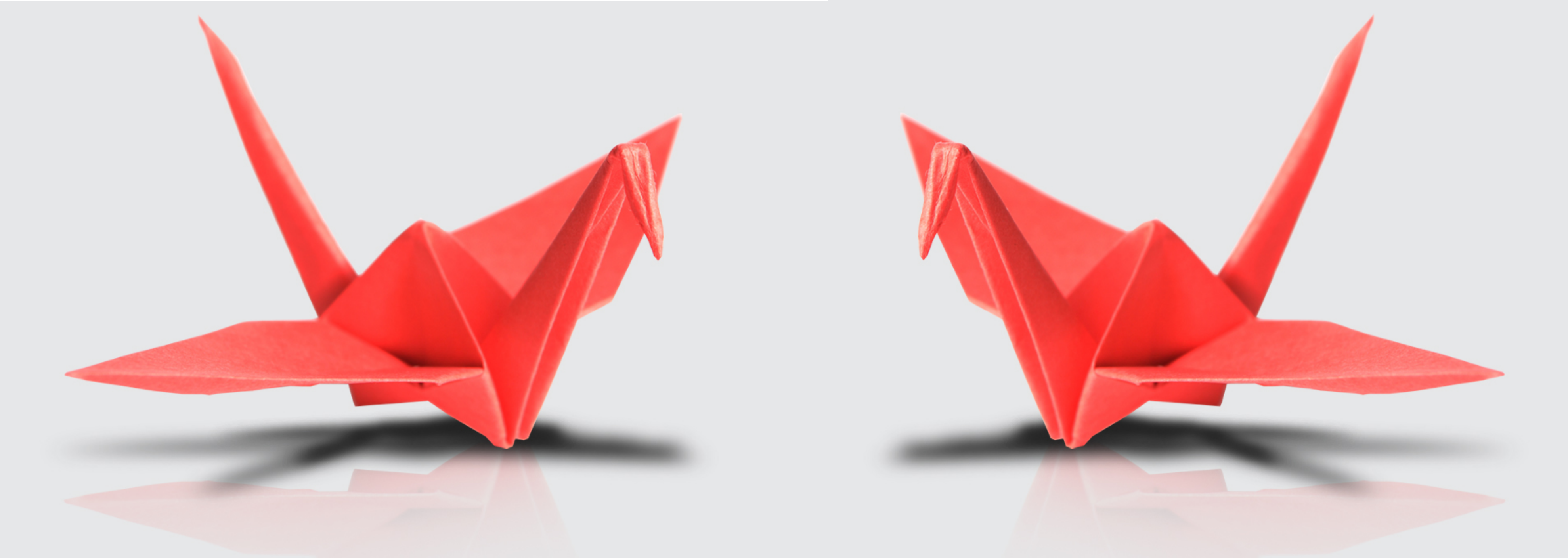


Beyond convexity

Prof Jessica James, Commerzbank

Introduction

Super-long dated issuance has grown

- The recent record low yield environment has meant that there has been appetite for issuance and purchase of super-long bonds of up to a century tenor, as these at least bear adequate coupons
- However, for these long dated tenors, the variation of bond price as bond yield changes becomes unintuitive
- Issuers and investors are familiar with the concepts of duration and convexity
- Duration is related to the first derivative of the bond price with respect to yield, and models the price sensitivity to yield changes as linear. Convexity is related to the second derivative, and models a degree of non-linearity
- For super long dated bonds the price-yield sensitivity needs more than these two terms, however. We need terms beyond convexity.

Bond Value and Bond Return

Distinction between value and return becomes important

- Opposite we define the Present Value (PV) of a bond and the return of a bond B_r
- c = annualised coupon (in percent e.g. 2% would be c= 0.02), y = current yield (in percent), and n is the tenor of the bond in years.
- The distinction between bond value and bond return is very important for super-long bonds, whereas with shorter tenors it is less relevant.
- PV is the sum of the discounted coupons plus the discounted final cashflow of principal plus coupon. Bond return is often expressed as a percentage and depends on the underlying change in yield
- A change in yield of 1 basis point is typically being assumed (DV01) but this does not have to be so.

$$PV = \sum_{i}^{n-1} \frac{c}{(1+y)^i} + \frac{1+c}{(1+y)^n} \qquad [1]$$

$$B_r = \frac{\Delta PV}{PV} \qquad [2]$$

Source: Bloomberg, Commerzbank

Duration

Linear approximation

- An investor buying a bond will be focussed on its sensitivity to changes in underlying yields; a high sensitivity would suit a short-term view, while stability will appeal for a longer term investment.
- The primary tool for estimating this sensitivity is the Modified Duration (ModD).
- ModD is a measure of a bond's sensitivity to changes in yield; it can also be interpreted as a number similar to the remaining lifetime of the bond, in years, particularly for low coupon values.
- Because this property is convenient and intuitive it is the likely reason behind most definitions of ModD which include a minus sign and a factor of 100
- The minus sign captures the fact that as yields go up prices go down, and the factor of 100 converts a fractional value to a number close to the tenor in years

$$ModD = -\frac{100}{PV}\frac{\mathrm{d}PV}{\mathrm{d}y} \qquad [3]$$

Source: Bloomberg, Commerzbank

Convexity

First non-linear approximation

- Duration is not the whole story and always underestimates the change in return for a given change in yield, because the graph of return against yield is not linear, but has a convex shape.
- This curvature is often represented by a second term referred to as convexity.
- A bond of low duration but high convexity will become more sensitive to yield changes as those changes get larger than the simple, linear duration approximation would imply.
- The convexity term is not always defined in the same way and its use is often more qualitative than quantitative. However, it always includes the second derivative of price with respect to yield
- [3] and [4] are similar to the first two terms in a Taylor expansion, which is a way of approximating any complicated function by a series of simple terms

$$C = \frac{1}{PV}\frac{\mathrm{d}^2 PV}{\mathrm{d}y^2} \qquad [4]$$

Source: Bloomberg, Commerzbank

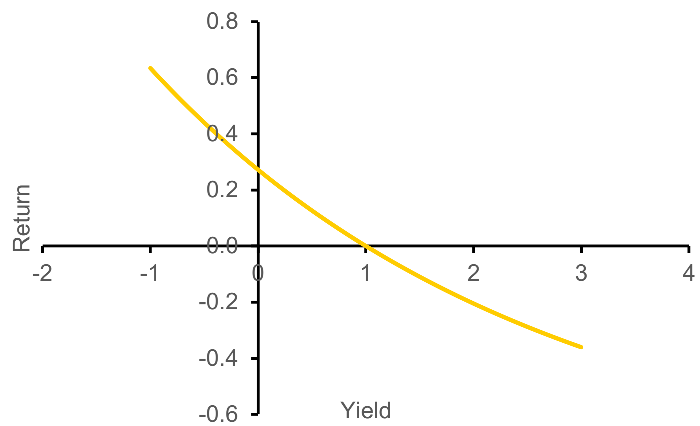
Calculating bond return

Consider a 30y and a 100y bond

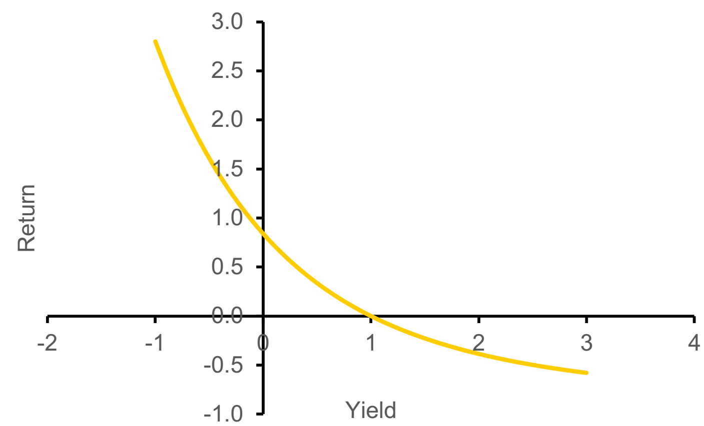
Below we graph the return of a bond with given tenor and coupon. We can then see immediately how the return varies as the yield moves away from the starting yield (taken to be 1% in the examples below, with a range of +/- 2 percentage points). Here we show the return as a function of final yield for 30 and 100 year bonds with coupons of 1% and 2%.

Even at a glance, the 100 year bonds have a greater curvature (convexity) but the reader should also note the scale on the y-axis which changes significantly between the two sets of bonds. Is convexity really enough?

30y bond, coupon 2%



100y bond, coupon 2%



Source: Commerzbank Research

Bond return formulae

Linear approximation

- Equation [1] is just the sum of a geometric progression. Using the standard formula for such a sum we can write the Present Value in the form opposite [5]
- [7] is the original Taylor expansion for the bond return, where y is the yield in %, Δy is the change in yield from the starting value
- The first term in [7] is the origin of Duration, while the second is the origin of Convexity
- [1] and [5] are identical, but [5] is more useful and means we can explicitly derive the various derivatives of bond returns
- The paper where we published these expressions is the first time to our knowledge that they have been derived

$$PV = \sum_{i}^{n-1} \frac{c}{(1+y)^i} + \frac{1+c}{(1+y)^n} \qquad [1]$$

$$PV = cV\left(\frac{1-V^n}{1-V}\right) + V^n \qquad [5]$$

$$V = \frac{1}{1+y} \qquad [6]$$

$$\frac{\Delta PV}{PV} = \frac{1}{PV}\frac{\mathrm{d}PV}{\mathrm{d}y}\Delta y + \frac{1}{2}\frac{1}{PV}\frac{\mathrm{d}^2 PV}{\mathrm{d}y^2}(\Delta y)^2 + \frac{1}{6}\frac{1}{PV}\frac{\mathrm{d}^3 PV}{\mathrm{d}y^3}(\Delta y)^3 + \frac{1}{24}\frac{1}{PV}\frac{\mathrm{d}^4 PV}{\mathrm{d}y^4}(\Delta y)^4 + \cdots \qquad [7]$$

Source: Bloomberg, Commerzbank

Formulae for derivatives

Though these are initially complex, patterns may be discerned.

$$\frac{\mathrm{d}PV}{\mathrm{d}y} = -nV^{n+1} + \frac{cV^2}{(V-1)^2}[-nV^{n+1} + (n+1)V^n - 1]$$

(8)

$$\frac{\mathrm{d}^2PV}{\mathrm{d}y^2} = n(n+1)V^{n+2} + \frac{cV^3}{(V-1)^3}[n(n+1)V^{n+2} - 2n(n+2)V^{n+1} + (n+1)(n+2)V^n - 2]$$

(9)

$$\begin{aligned}\frac{\mathrm{d}^3PV}{\mathrm{d}y^3} &= -n(n+1)(n+2)V^{n+3} \\ &\quad + \frac{cV^4}{(V-1)^4}[n(n+1)(n+2)V^{n+3} - 3n(n+1)(n+3)V^{n+2} + 3n(n+2)(n+3)V^{n+1} \\ &\quad - (n+1)(n+2)(n+3)V^n + 6]\end{aligned}$$

(10)

$$\begin{aligned}\frac{\mathrm{d}^4PV}{\mathrm{d}y^4} &= n(n+1)(n+2)(n+3)V^{n+4} \\ &\quad + \frac{cV^5}{(V-1)^5}[n(n+1)(n+2)(n+3)V^{n+4} - 4n(n+1)(n+2)(n+4)V^{n+3} \\ &\quad + 6n(n+1)(n+3)(n+4)V^{n+2} - 4n(n+2)(n+3)(n+4)V^{n+1} \\ &\quad + (n+1)(n+2)(n+3)(n+4)V^n - 24]\end{aligned}$$

(11)

Value of terms as y →0

Special care has to be taken as yield approaches zero

$$\lim_{y\to 0} \frac{\mathrm{d}PV}{\mathrm{d}y} = -n - \frac{cn}{2}(n+1)$$

(12)

$$\lim_{y\to 0} \frac{\mathrm{d}^2PV}{\mathrm{d}y^2} = n(n+1) + \frac{cn}{3}(n+1)(n+2)$$

(13)

$$\lim_{y\to 0} \frac{\mathrm{d}^3PV}{\mathrm{d}y^3} = -n(n+1)(n+2) - \frac{cn}{4}(n+1)(n+2)(n+3)$$

(14)

$$\lim_{y\to 0} \frac{\mathrm{d}^4PV}{\mathrm{d}y^4} = n(n+1)(n+2)(n+3) + \frac{cn}{5}(n+1)(n+2)(n+3)(n+4)$$

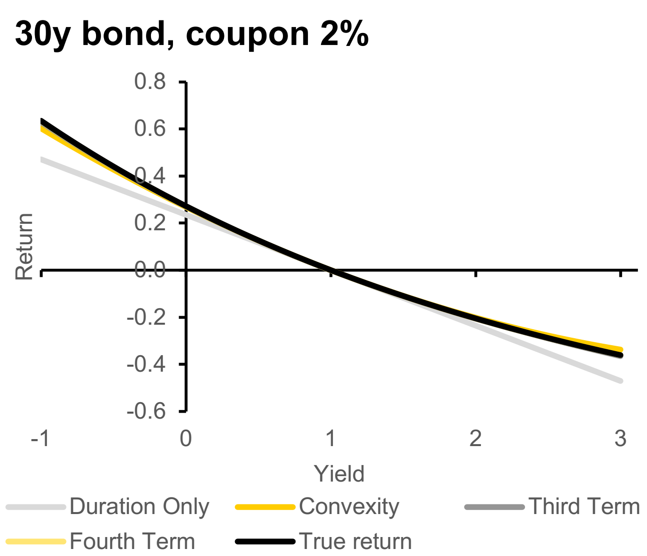
(15)

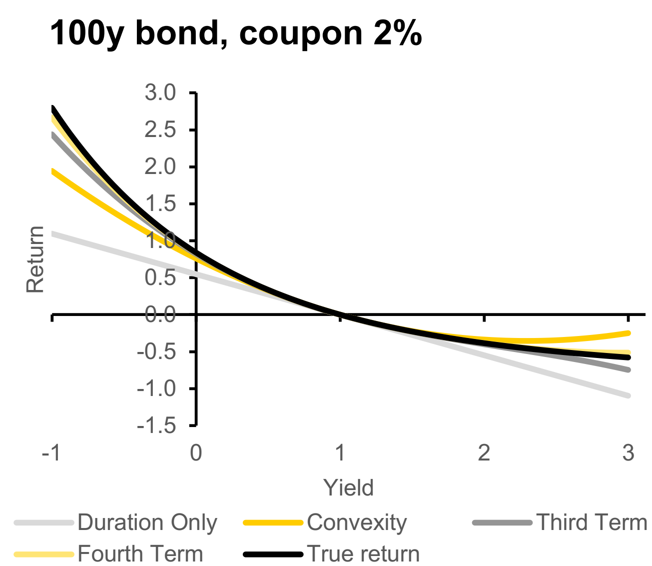
Bond return and its components

Consider a 30y and a 100y bond

Below we graph the actual return of the 30y and 100y bonds, and also the successive approximations. One can immediately see that the convexity approximation for 30 year bonds is strongly justified, even over significant changes of yield. However, for 100 year bonds it is noticeably inaccurate for yield changes above one percentage point either up or down.

In particular, the Convexity term causes the return to increase with increasing yield for large positive yield changes, which is clearly wrong. Even when we include a third term, there is still a visible error which is finally rendered unimportant by the addition of the fourth term.





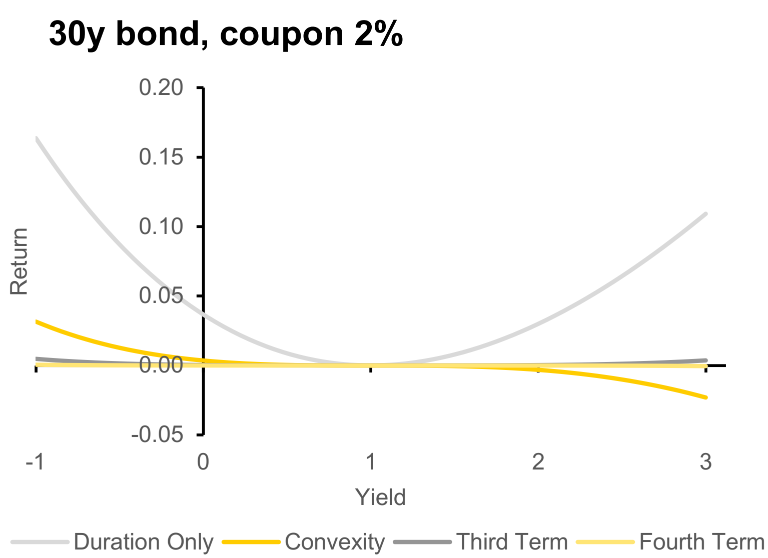
Source: Commerzbank Research

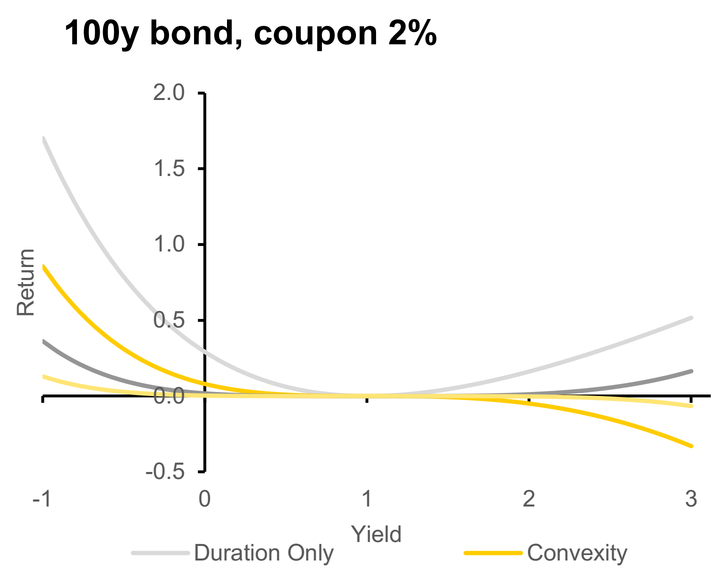
Bond return and Residuals

Differences between approximations and the true value show in detail the effect of each term

Note the very different scales on the 30 year and 100 year graphs. For the 100 year case the third and fourth terms are essential for accurate results. Theshapes of the residuals are as we would expect, with convexity being quadratic, leaving a positive residual at one end and negative at the other, which is then corrected by the cubic form of the third term, itself then further improved by the quartic fourth term.

In practical terms, the analysis confirms the well-known positive property from convexity (as yields fall, present value gains accelerate, as yields rise, they decelerate). Considering the higher terms, this property is being amplified for falling yields, but it is being reduced for rising yields.





Source: Commerzbank Research

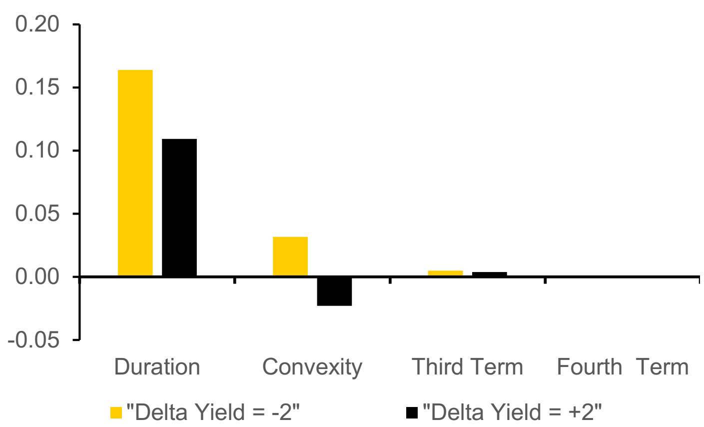
Cases of rising and falling yields

Positive and negative yield changes are very different

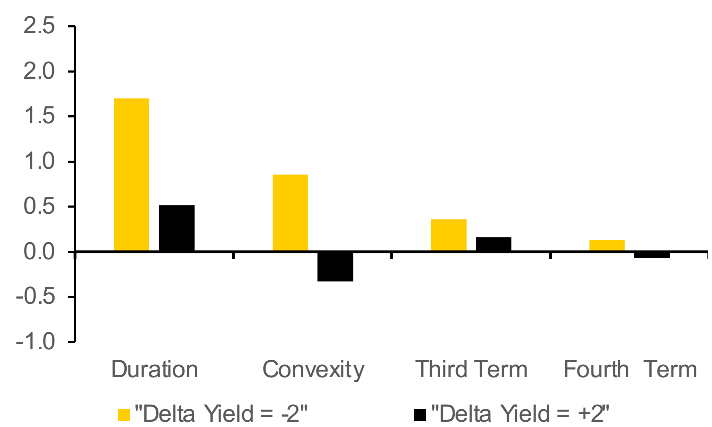
To understand the different effects of positive and negative yield changes, we have plotted the charts below. These are the residuals for the different terms at a yield change of +2 and -2 percentage points. In effect they are looking at the very ends of the graphs above.

They show that the approximation is always below the true curve for negative yield changes (in gold) but alternates above and below for successive terms for positive yield changes (in black).

30y bond, coupon 2%



100y bond, coupon 2%



Source: Commerzbank Research

Impact of these results

Familiar intuition is no longer enough

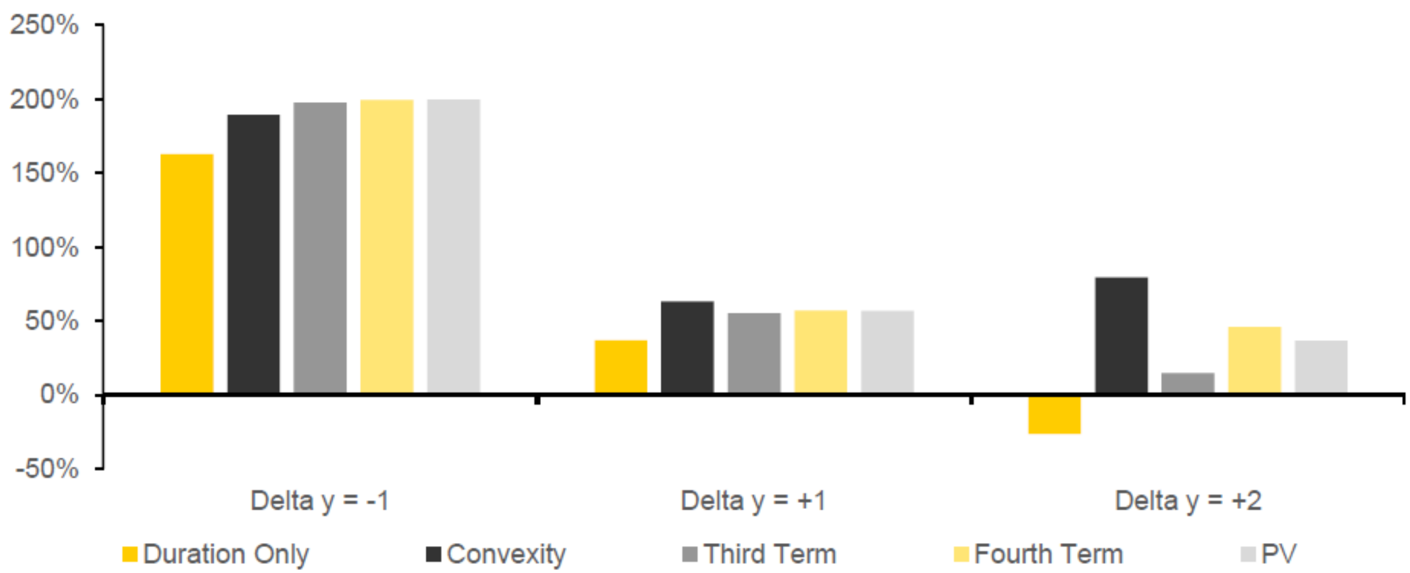
- It would be unreasonable to expect that the third and fourth terms in this series would provide much useful intuition about bond value! But they are important in the extreme conditions of today's market, just as Convexity is important for bonds of 30 year tenor.
- In the particular circumstances of 100 year bonds issued in a low-yield environment, the expectations an investor might have from an understanding of Duration and Convexity become less useful, even potentially misleading.
- The expression we have derived here allow us to identify both conditions under which further analysis is needed, and exactly how to do that.
- As a rule of thumb, for a 100 year bond, its value under changes in yield of greater than one percentage point will be poorly approximated unless terms beyond convexity are taken into account.
- In terms of tenor, 50y and more will need to consider terms beyond convexity in markets like today.

Convergence to present value

Positive and negative yield changes are very different

- Consider the value of a 100 year bond of 1% coupon and a starting yield of 1%. A change in yield of positive two percentage points from +1% for a 100 year bond is a complex situation. The final PV is small and so the errors are proportionately larger.
- The correction terms alternate in sign - the approximation first undershoots (goes negative!), then overshoots as Convexity is added in. For a change in yield of positive one percentage point, the oscillation is still present but the errors are much smaller. These effects can be seen clearly in the graph below.

Convergence to Present Value for Different Yield Changes (100y bond, Coupon 1%)



Source: Commerzbank Research

What really happened?

Investors who bought century bonds may have been 'long and wrong'

Investors who have been 'long' ultra-long bonds over recent months have incurred substantial losses on their positions. Ultra-long maturities inherently carry greater duration risk, but losses attributed to the latest rise in yields still stand out. NRW's century bonds are a prime example.

A long position e.g. in the NRW Mar2119 initiated at the Covid-induced price-peak would have incurred a loss of more than 70% today, after a yield increase of 2.5 percentage points (chart below)..

Extreme price moves in ultra-long bonds
NRW 2.15% Mar2119 price and yield, in %

Source: Bloomberg, Commerzbank Research

The value of higher terms

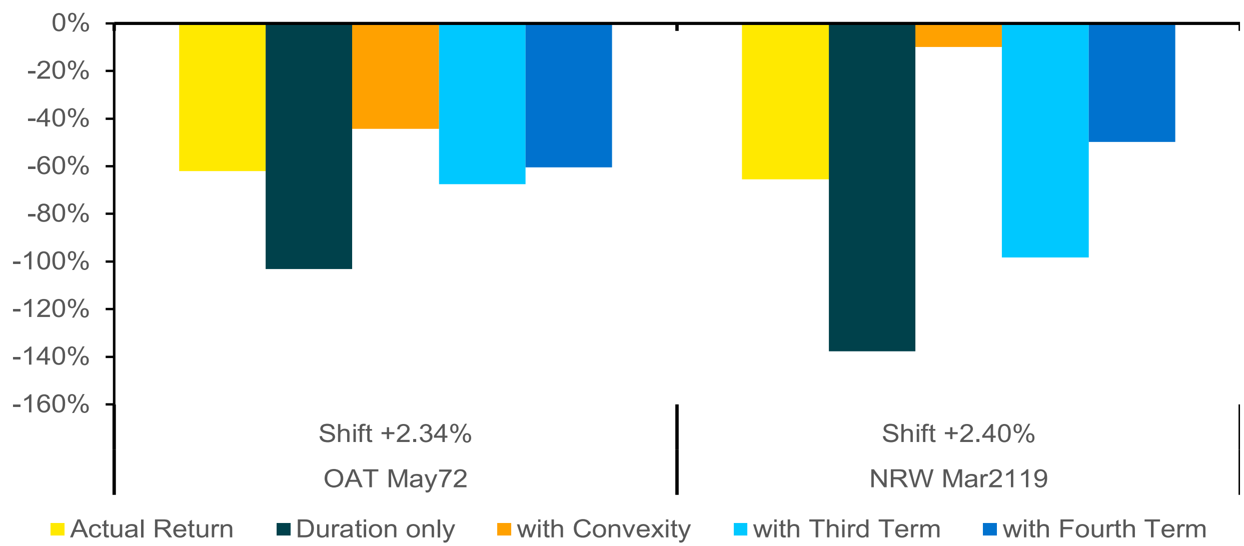
OAT and NRW examples

The chart below shows the realised return (yellow) on the 50y OAT May72 and the 100y NRW Mar2119. For the sake of argument, we assume that the bonds were bought at the "worst possible time", i.e. in January 2021 and in March 2020, respectively, to generate the largest possible yield delta.

Duration alone, would have vastly over-estimated the loss on both the 50y as well as the 100y bond. Including convexity into the equation still provides a poor estimate of the bonds' actual returns. Only when including the third (and for the 100y bond the fourth) Taylor term, the predictions become reasonably accurate.

Duration & Convexity are not enough!

Actual/approximate price changes*



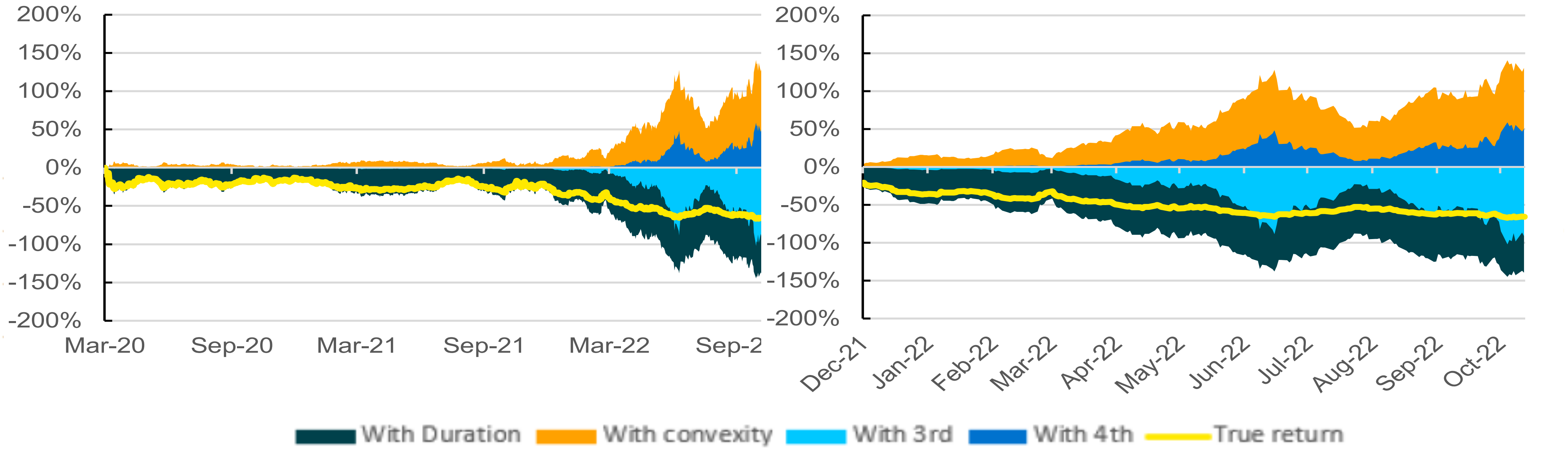
Source: Bloomberg, Commerzbank Research *Actual and approximated change in clean price for given yield shift. OAT72 had a clean price of about 97.5 while NRW2119 had a clean price of above 200 when positions were initiated.

When did higher terms kick in?

NRW bond history

Higher terms have become essential to explain moves in 2022

Contributions to PV changes since Mar 2020 and Dec 2021, for NRW Mar2119



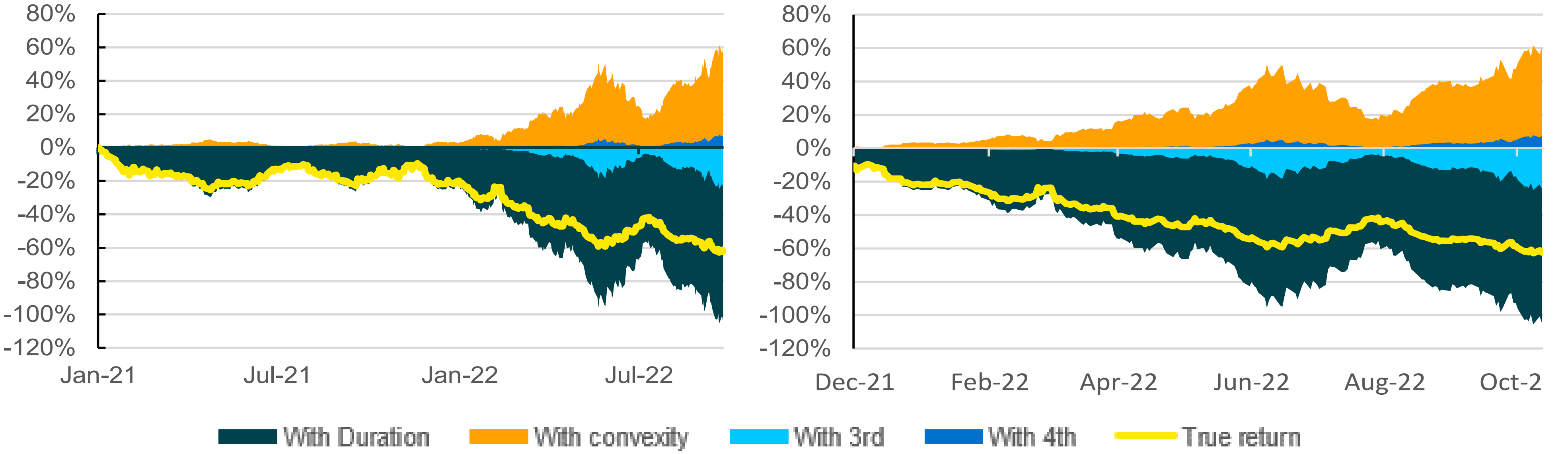
Source: Bloomberg, Commerzbank Research

When did higher terms kick in?

OAT bond history

50y bonds also feel the effects of higher terms

Contributions to PV changes since Jan 2021 and Dec 2021, for OAT May2071



Source: Bloomberg, Commerzbank Research

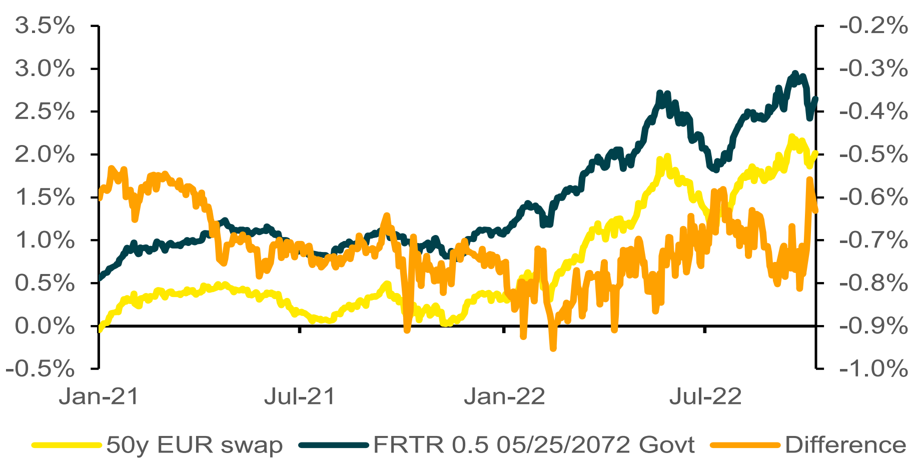
Can we hedge them?

OAT and NRW with 50y swap rate

Below we plot the yields of both the bonds and the 50y swap rate, with their difference on the right hand axis. Of course the yields are highly correlated but the spread between them varies. The curve is very loosely directional with the spread tightening as yields rise (50y swap rate rising more than 100y bond yield).

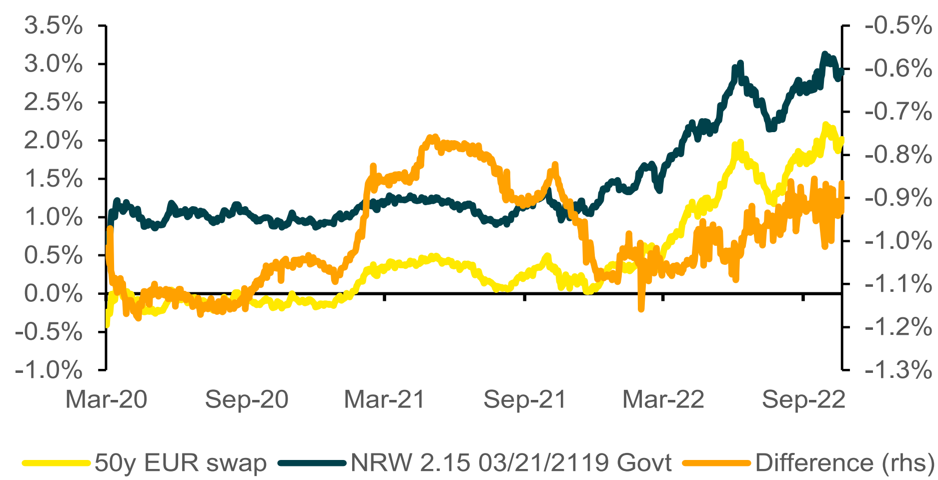
The swap spread widening over the last two years has amplified this effect with swap rates rising more than NRW yields. For the 50y OAT, the swap spread is usually inversely correlated with yields, but since early 2021 the OAT yield actually rose slightly more than the 50y swap rate. Our observation period is from 12th March 2020 for NRW and 25 Jan 2021 for OAT

OAT Bond-Swap correlation
Yields in %,



Source: Bloomberg, Commerzbank Research

NRW Bond-Swap correlation
Yields in %,



Source: Bloomberg, Commerzbank Research

The hedge is effective!

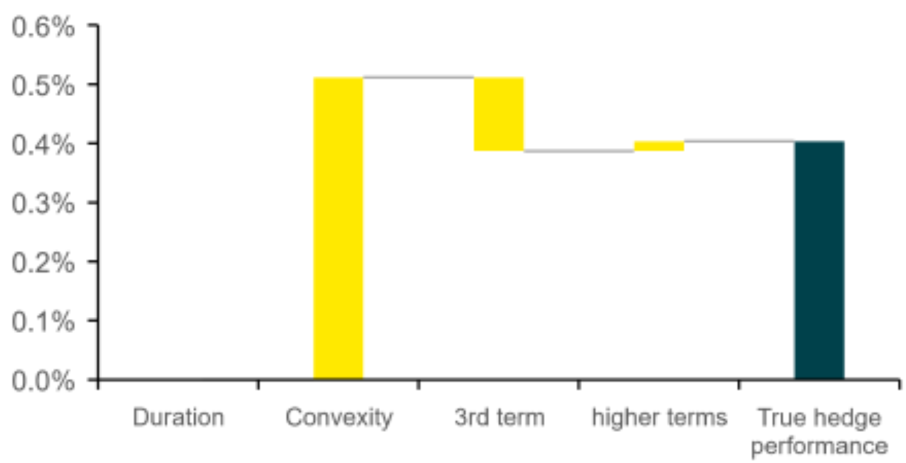
Hedged performance, different terms

We assume a duration weighted hedge, and analyse the effect of a +1 percentage point increase in yield, and break it down into its different contributions. Below we show the effects of such a shift for bonds with tenors and coupons the same as the NRW and OAT bonds, and we model the 50y swap hedge by looking at its present value change due to the yield shift. If the hedge were perfect, the bars would have zero value.

On the whole it's good news! Overall the hedge has performed well, with only a few percent hedge error for even the longer dated bond. In particular the value-change of the maturity-matched hedged 50y OAT is minor. Second of all, the performance is positive in both positions, significantly so in the hedged 100y position.

Hedged OAT performance, +1ppt yield shift

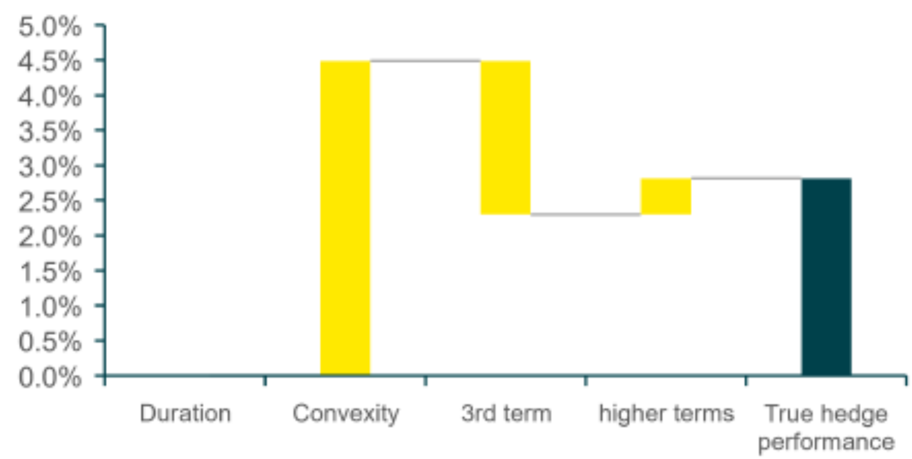
Hedged with 50y swap, duration weighting, in % notional



Source: Bloomberg, Commerzbank Research

Hedged NRW performance, +1ppt yield shift

Hedged with 50y swap, duration weighted, in % notional



Source: Bloomberg, Commerzbank Research

But why?

Where is this coming from?

- The duration terms cancel out by construction - we have duration weighted the swap.
- Also, the durations were fairly similar to begin with, a function of the fact that the coupon on the bonds reduces the duration relative to that of the swap.
- However, the greater convexity of the bond is overwhelming.
- The 'long convexity' position is thus responsible for the positive performance, however, the the third term reduces the convexity effect by a good degree.
- This means that the hedge becomes more accurate, while reducing the positive performance.

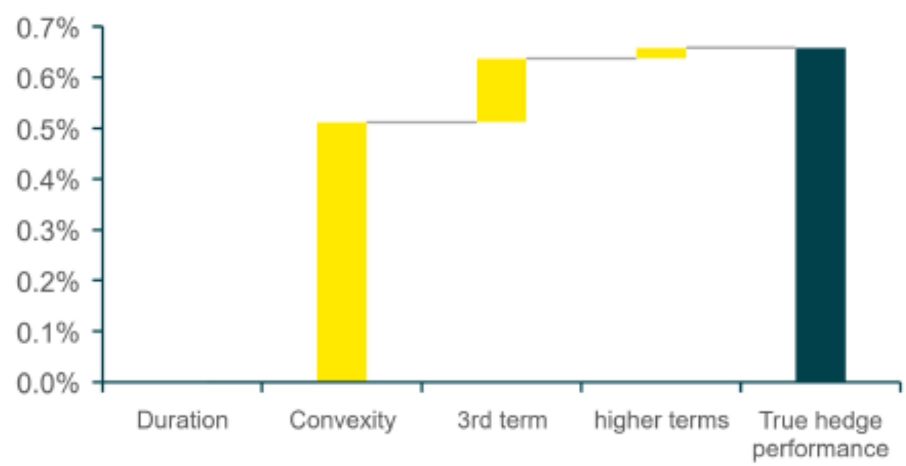
What if yields fall?

Still a good hedge

Also here, the long convexity position would create a positive performance (as yields fall, the duration of the long bond position rises by more than the duration of the swap). In contrast to a rising yield environment, however, as shown here, when yields fall, higher terms beyond convexity all have the same sign and serve to amplify the effects.

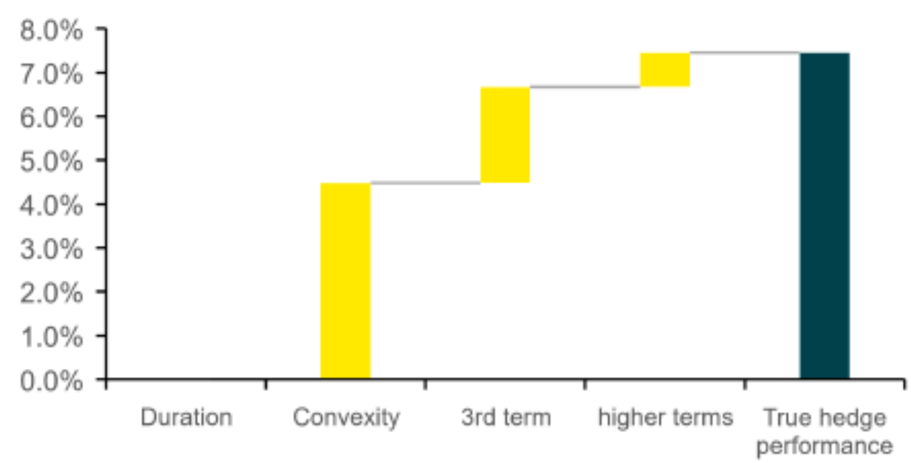
We see that the hedge error for the century bond is twice that of the case of the yield increase, and moreover including only duration and convexity effects underestimate the error by a factor of two. The 50y OAT bond in contrast remains well hedged.

Hedged OAT performance, -1% yield shift
Hedged with 50y swap, duration weighting, in % notional



Source: Bloomberg, Commerzbank Research

Hedged NRW performance, -1% yield shift
Hedged with 50y swap, duration weighting, in % notional



Source: Bloomberg, Commerzbank Research

Historical hedged results

Using historical yield changes, duration weighted hedges

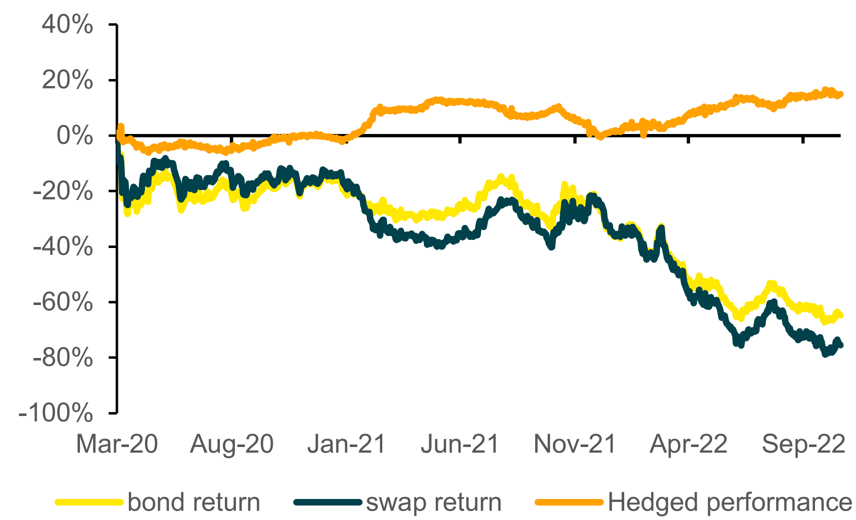
For the NRW bond, duration was 58.8 while that of the swap was 55.7 (it was greater than 50 because it stared with a negative yield, -0.413% on 12th Mar 2020), leading to a hedge ratio of 1.06.

For the OAT bond, duration was 44.0 at its peak on 25th Jan 2021, and at that point the 50y swap duration was 50.62, leading to a hedge ratio of 0.87. These ratios mean that the hedged performance below is not exactly the difference between the bond and the swap return.

Hedged returns for OAT
Duration weighted hedge with 50y swap

Source: Bloomberg, Commerzbank Research

Hedged returns for NRW
Duration weighted hedge with 50y swap



Source: Bloomberg, Commerzbank Research

Conclusions

Higher terms are important, but can be understood

- Super long bonds cannot be only understood using familiar intuition from duration and convexity; higher terms are needed
- Rising and falling yield environments are very different
- Paying 50y swaps to hedge 100y bonds may not create a perfect hedge. However, the resulting position has the advantage of a positive expected performance in both a rising and a falling yield environment due to the positive convexity.
- The third term of the Taylor expression reduces the performance in a rising yield environment and it amplifies the perfromance in a falling yield environment.
- The risks come from non-parallel curve shifts or swap spread widening (bond yield rising more or falling less than the swap rate). As the super-long curve is loosely directional (flattening as yields rise), the risks appear larger in a falling yield environment.

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