ON THE MATHEMATICS OF MACAULAY'S DURATION: A NOTE

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I. Introduction

The purpose of this note is to examine mathematically the behavior of a bond's duration in response to changes in the market yield, the bond's term to maturity and its coupon rate. Although the nature of the relationships between duration and yield, duration and maturity, and duration and coupon are known to financial economists, a review of the literature on the subject reveals that the exact form of these relationships has generally been investigated via numerical evaluation (See Fisher and Weil [4]), computer simulation (see Haugen and Wichern [6]), or casual analytical observation (see the appendix in Whittaker [12]). The absence of a systematic mathematical approach to the problem may be partly due to the somewhat intractable form of the definitional expression of a bond's duraton given in (1) below, particularly in the case of the relationship between duration and term to maturity.

The concept of a bond's duration was first expounded by Macaulay [9] and, independently, by Hicks [7][1]. Essentially, Macaulay [9] argued that a bond's term to maturity is a poor proxy-measure of its price volatility. He then suggested a new measure which he called duration and which he shows to have properties making it a superior measure of a bond's "longness". Later, Hopewell and Kaufman [8] proved that a bond's duraton is proportional to its elasticity and hence is a good proxy for the bond's interest-rate risk. The usefulness of the concept of duration goes beyond it being a proxy measure of bond price volatility. It can also be used as a tool to control and reduce the interest-rate risk born by financial institutions. By matching the average duration of their asset-portfolio to that of their liability-portfolio, these institutions can practically hedge or "immunize" their bond investment. The interested reader is referred to the work of Redington [10], Fisher and Weil [4] and the more recent paper of Gushee [5]. For further detail on the historical development of the concept of duration and its applications to risk management see Weil [11], and Whittaker [12].

A bond's duration was defined by Macaulay [9, p. 48] as the weighted average number of years until the bond's cash flows occur, where the weights used are the present values of each payment relative to the bond's price. We can express Macauley's definition of a bond's duration as:

$$D(n,io,i) = \frac{\sum_1^n i_o tv^t + nv^n}{P/F} = \frac{i_o\sum_1^n tv^t + nv^n}{i_o\sum_1^n v^t + v^n} \tag{1}$$

where D = bond's duration

P = bond's price

F = bond's par-value or principal

i_o = bond's coupon-rate

n = bond's term to maturity

i = bond's yield to maturity or market yield

$v = (1+i)^{-1}$ = one period discount factor at rate i

In the next section we modify the standard duration expression in (1) into a more tractable form. This alternative expression will then allow us to examine in Section III the maturity-behavior of duration, that is, the response of duration (D) to changes in maturity (n) with the coupon-rate (i_o) and the yield (i) remaining the same. In section IV and V we investigate the coupon-behavior and the yield-behavior of duration, respectively. The last section contains concluding remarks.

II. Duration: A More Tractable Expression

In this secton we derive an alternative expression for a bond's duration which will facilitate the examination of both the maturity-behavior and the coupon-behavior of duration. We will see, however, that the examination of the yield-behavior of duration can be carried out more easily using the original definitional expression of duration given in (1).

The partial derivative, with respect to yield, of the bond's price given in the denominator of (1) is:

$$\frac{\partial P/F}{\partial i} = - v(i_o \sum_1^n tv^t + nv^n) \tag{2}$$

Using (2), the duration given in (1) can be rewritten as:

$$D = - (F/P) \left(\frac{\partial P/F}{\partial i}\right) v^{-1} \tag{3}$$

Alternatively the bond's price can be expressed as[2]

$$P/F = (i_o + (i-i_o)v^n)i^{-1} \tag{4}$$

and hence:

$$\frac{\partial P/F}{\partial i} = - [(i_o + (i-i_o)v^n)i^{-1} + ((i-i_o)v^n-v^n)]i^{-1} \tag{5}$$

$$= -[i_o a + n(i-i_o)v^{n+1}]i^{-1}$$

where "a" is the present value of an n-period one-dollar annuity at a rate i such as $a = (1 + v^n)i^{-1}$.

Substituting (5) and (4) in (3) we get:

$$D(n,i_o,i) = \frac{(1+i)a\ i_o + n(i-i_o)v^n}{i_o + (i-i_o)v^n} \tag{6}$$

which is an expression of a bond's duration that is easier to analyze than the definitional expression in (1), particularly when we examine the maturity-behavior and the coupon-behavior of duration. The advantages of expression (6) over expression (1) are: (i) the summation signs have been eliminated which greatly simplifies the examination of the maturity-behavior of duraton, (ii) the term $(i-i_o)$ appears in (6) which allows us to explicitly examine the differential effects of changes in maturity on the duration of bonds selling above par $(i_o<i)$ or below par $(i_o>i)$, (iii) the numerator of (6) is its demoninator in which the first term is multiplied by $(1+i)a$ and the second term multiplied by n.

We will also find it convenient to rearrange (6) in the following manner:

$$\frac{D}{n} = \frac{\alpha i_o + (i-i_o)v^n}{i_o + (i-i_o)v^n}, \text{ where } \alpha=(1+i)a/n \tag{7}$$

According to (7) the ratio of a bond's duraton to its maturity is such as the numerator is the denominator with its first term multiplied by $\alpha = (1+i)a/n$.

III. The Maturity-Behavior of Macaulay's Duration

Theorem 1 "A bond's duration is equal to its maturity if and only if it is a zero-coupon bond (pure discount issue) or a one-period-coupon bearing bond."

Proof: According to (7), D/n is equal to one if and only if $i_o = 0$ or $\alpha = 1$. The former case is that of a zero-coupon bond. The latter case implies

$(1+i_o)a=n$ which is satisfied only if $n=1$, that is, if the bond is a one-period coupon-bearing issue. Q.E.D.

Theorem 2: "The duration of a coupon-bearing bond with a finite maturity of more than one period ($1<n<\infty$) has a duration which is shorter than its term to maturity."

Proof: For a coupon-bearing bond with $1<n<\infty$ we have[3] $\alpha<1$ and therefore the numerator of D/n in smaller than its denominator. Hence $D/n<1$: maturity exceeds duration. Q.E.D.

Theorem 3: "The duration of a perpetual bond ($n=\infty$) is equal to $(1+i^{-1})$ irrespective of its coupon rate."

Proof: As n goes to infinity both nv^n and v^napproach zero and "a" approaches i^{-1}. Referring to (6) we can see that the limiting value of D becomes $(1+i^{-1})$ as the term to maturity goes to infinity."

Corollary: "The duration of a coupon-bearing bond approaches the limit $(1+i^{-1})$ as the bond's maturing is lengthened to infinity"

Theorem 4: "The duration of a coupon-bearing bond selling at par (io=i) or above par (io>i) increases monotonically with its term to maturity and approaches $(1+i^{-1})$ as the term to maturity goes to inifinity."

Proof: This theorem can be proved by examining the sign of the partial derivative of D(n) with respect to n. This exercise in somewhat more difficult than proving the preceding three theorems because the sign of $\partial D/\partial n$ is not readily determined. We want to prove that $\partial D/\partial n>o$ if $i_o \geq i$. Taking the derivative of (6) with respect to n we get:

$$\frac{\partial D}{\partial n} = \frac{v^n[io(1+i)\log(1+i) + io(i-io)+(i-io)^2v^n - nio(i-io)\log(1+i)]}{[io + (i-io)v^n]^2} \qquad (8)$$

The second and third terms in the numerator of (8) can be rearranged such as:

$$io(i-io) + (i-io)^2v^n = (i-io)iv^n + io(i-io)ia$$

and hence the terms between brackets in the numerator of (8) can be rewritten as:

$$i_o(1+i)\log(1+i) + (i-i_o)iv^n - i_o(i-i_o)(n\log(1+i) - ia) \qquad (9)$$

We will now prove that the sum of the first and second terms in (9) is always positive. To prove this, note that log (1+i) is larger than $i/(1+i)$ 4 and hence we have:

$$(1+i)\log(1+i) = i+e \quad \text{with} \quad e>0$$

Consequently the first and the second terms in (9) can be expressed as:

$$i_o(i+e) + i^2v^n - i_oiv^n = i_oi(1-v^n) + i_oe + i^2v^n > 0.$$

If a bond sells at par ($i_o=i$) then the third term in the numerator of (8) in zero and $\partial D/\partial n>0$.

We now prove that the sign of the last term in (9) is that of (i_o-i). Consequently if the bond sells above par ($i_o>i$) the last term in the numerator of (8) is positive and, again, $\partial D/\partial n>0$. We can write:

$$n\log(1+i) - ia = n\log(1+i) + (1+i)a.i/(1+i)$$

and since $n>(1+i)a$ and $\log(1+i)>i/(1+i)$ it follows that $(n\log(1+i)-ia)$ is positive and that the third term in (9) has the sign of (i_o-i). Q.E.D.

<u>Theorem 5</u> "The duration of a coupon-bearing bond selling below par ($i_o<i$) reaches a maximum before maturity reaches infinity and then recedes toward the limit $(1+i^{-1})$."

<u>Proof</u>: When the bond sells below par ($i_o<i$) the last term in (9) is negative and $\partial D/\partial n$ may be zero or negative. Consequently D(n) may have one or more extrema. First let us show that there exists a value of n for which

$\partial D/\partial n \leqq 0$. The sum of the terms between brackets in the numerator of (8) is zero or negative if:[5]

$$n \geqq \frac{i_o(1+i)\ \log(1+i)\ +\ (i-i_o)(i_o+(i-i_o)v^n)}{i_o(i-i_o)\log(1+i)} \tag{10}$$

Since $[(1+i)/(i-i_o)]>1$ it follows that the RHS of (10) is larger than one and hence $\partial D/\partial n$ can be zero or negative. When $\partial D/\partial n=0$ we have:

$$\frac{\partial^2 D}{\partial n^2} = \frac{(i-i_o)v_o^n \log(1+i)}{i_o + (i-i_o)v^n} < o$$

It follows that D(n) has a maximum when the bond sells below par $(i_o<i)$. We now have to establish that the maximum value of duration, D_{max}, exceeds the limiting value of duration $D_{lim} = (1+i^{-1})$. The values of n which $D(n) \geqq D_{lim}$ is satisfied are:

$$n \geqq \frac{1+i}{i-io}$$

Consequently when a bond sells below par $(i_o<i)$ there exist values of n for which duration exceeds its limiting value $D_{lim} = (1+i^{-1})$. Note that if the bond sells either at par $(i_o=i)$ or above $(i_o>i)$ there are no finite value of n for which $D(n) \geqq D_{lim}$. Q.E.D.

Theorem 6 "The duration of a coupon-bearing bond selling below par reaches its maximum at a maturity directly related to the bond's coupon rate and inversely related to the market yield."

Proof: We have shown that the value of n for which D(n) intersects D_{lim} is $n^*=(1+i)/(i-i_o)$. We have:

$$\frac{\partial n^*}{\partial io} = \frac{1+i}{(i-io)^2} > 0 \text{ and } \frac{\partial n^*}{\partial i} = -\frac{1+i}{(i-io)^2} < 0$$

and therefore D_{max} is directly related to i_o and inversely related to i. Q.E.D.

Theorem 7 "The longer a bond's term to maturity, the greater the difference between its term and its duration."

Proof: Note that:

$$\frac{\partial(n-D)}{\partial n} = 1 - \frac{\partial D}{\partial n} > 0 \quad \text{since} \quad \frac{\partial D}{\partial n} < 1$$

$\partial D/\partial n$ is smaller than one because for $0<n<\infty$ we have $0<D/n<1$. Q.E.D.

IV. The Coupon-Behavior of Macaulay's Bond Duration

Theorem 8 "A bond's duration varies inversely with its coupon rate (except for one period and perpetual bonds)."

Proof: Simply take the partial derivative of (6) with respect to i_o:

$$\frac{\partial D}{\partial io} = \frac{i[(1+i)a - n]v^n}{[io + (i-io)v^n]^2} < 0$$

The above derivative is negative since for $1<n<\infty$ we have $(1+i)a<n$.

Q.E.D.

V. The Yield-Behavior of Macaulay's Bond Duration

Theorem 9 "The duration of a coupon-bearing bond is inversely related to its yield to maturity."

Proof: This theorem can be proved be determining the sign of D/ i. This sign can be more easily determined if we take the derivative of D(i) as expressed in (1) rather than (6). We have:

$$\frac{\partial D(i)}{\partial i} = \frac{-i_o v \Delta(n) + ni_o v^{n+1} \sum_1^n (n-t)v^t + i_o v^n \sum_1^n (n-t)tv^{t+1}}{[i_o+(i-i_o)v^n]^2} < 0$$

with $\Delta(n)=\sum_1^n t^2 v^t \sum_1^n v^t - \sum_1^n tv^t \sum_1^n tv^t > 0$

$\Delta(n)$ is positive since it is the difference between two positive terms, the first being larger than the second. The second and third terms in the numerator of $\partial D/\partial i$ are also positive and hence $\partial D/\partial i<0$. Q.E.D.

<u>Theorem 10</u> "The duration of a "zero-yield" bond is equal to $(1/2(n^2+n)i_o + 1)/(ni_o + 1)$."

<u>Proof</u>: We have, using (1):

$$\lim_{i\to 0} D(i) = \frac{i_o \sum_1^n t + 1}{i_o n + 1} = \frac{1/2(n^2+n)i_o + 1}{ni_o + 1} \text{ . Q.E.D.}$$

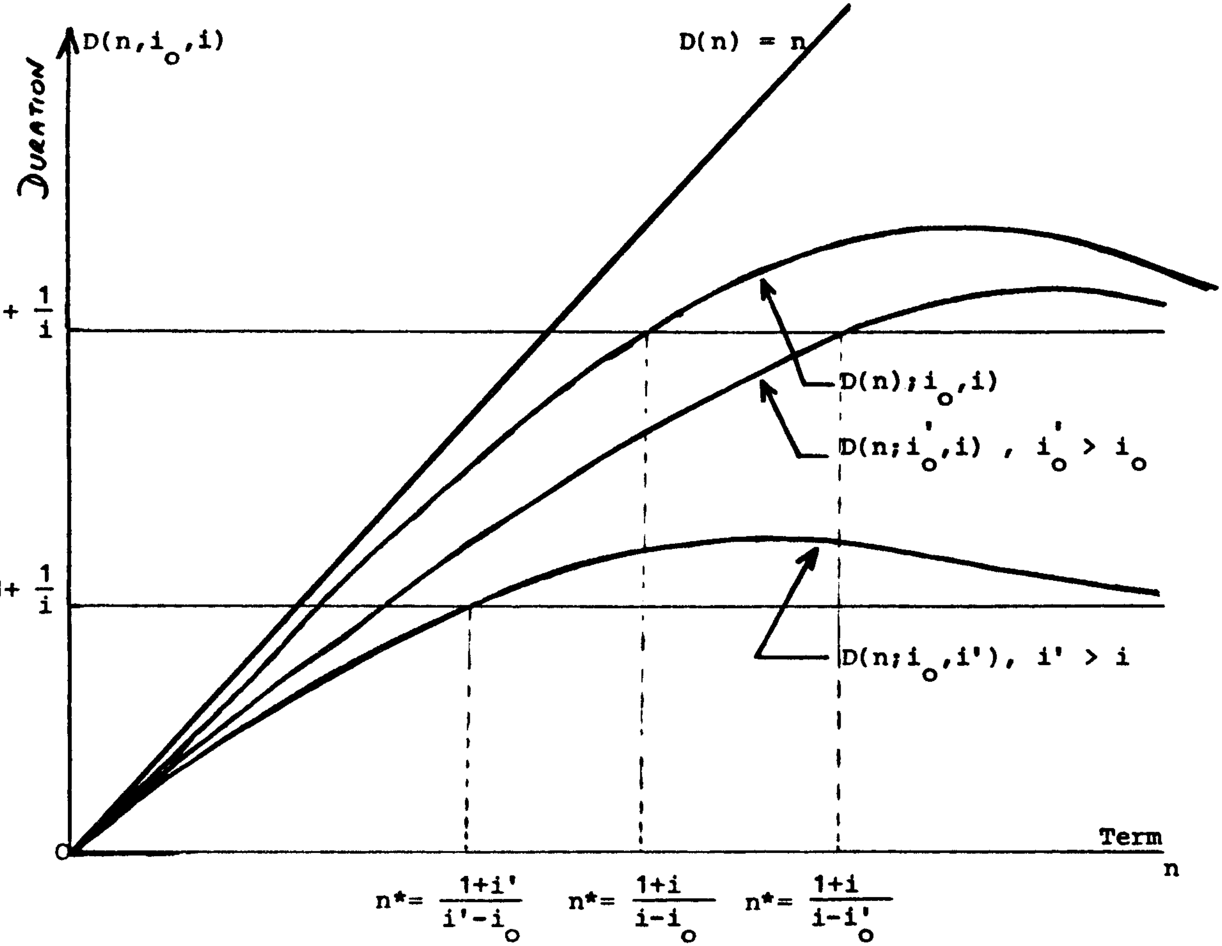
<u>Theorem 11</u> "A bond's duration approaches unity as the bond's yield approaches infinity."

<u>Proof</u>: The limit of $(1+i)a$ as $i \to \infty$ is one. The limit of $(i-i_o)v^n$ as $i \to \infty$ is zero. It follows from the expression of duration in (6) that the limit of $D(i)$ as $i \to \infty$ is equal to $(i_o/i_o)=1$. Q.E.D.

VI. Concluding Remarks

The purpose of this note was to examine mathematically the relationships between a bond's duration and its term, coupon and yield. A review of published work on the subject has revealed that these relationships have been generally examined in the past via numerical evaluation, computer simulation or casual analytical observation. The mathematical approach adopted in this note has been carried out with the help of a modified expression of a bond's duration which is more amenable to mathematical manipulations than Macaulay's original definitional expression for a bond's duration.

Most of the results established in this note are summarized in figure 1 for the case of a bond selling below par. Curve (1) depicts the original rela--tionship between duration and term given coupon (i_o) and yield (i). As coupon rises to i_o', curve (1) shifts to position (2). As yield rises to i', curve (1) shifts to position (3). The straight lines (1+1/i) and (1+1/i') are the asymptotic values of D(n) as $n \to \infty$. These asymptotes intersect the curves D(n) at terms n*.



- FIGURE 1 -

Shift of the original curve $D(n;i_o',i)$ as i rises to i_o' and as i rises to i'.

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Footnotes

1. In this note we focus on Macaulay's definition of duration. For alternative specifications, which take into account the term structure of interst rates, see the contributions of Bierwag [2], [3] and Cox, Ingersoll and Ross [1].

2. Note that $P/F = i_o(1-v^n)/i + v^n$ from which (4) is easily derived.

3. Note that $(1+i)a = \sum_1^n (1+i)^{-t+1} < n$ and hence $\alpha = (1+i)a/n < 1$.

4. This can be easily shown by expanding $\log(1+i)$ by Taylor's series.

5. Note that (10) implies that for a discount bond, duration achieves its maximum when:

$$n = \frac{1}{\log(1+i)} + \frac{1+i}{i-io} + \frac{i-io}{io(1+i)^n \log(1+i)}$$

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