Speed, Pitch, and Timing Errors in Tape Recording and Reproducing*

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Because tape is a plastic medium driven by a capstan in a complicated rolling process, an accurate specification of "tape speed" is not simple. However, it is shown that even a complete specification of tape speed alone is not adequate to specify the pitch and timing error because changes of the recorded wavelength due to tape length changes cause additional independent timing and pitch errors of up to 1.0 %. These are significant in comparison with the NAB tape speed tolerance of ±0.2 %. Measurement techniques are also reviewed.

0 INTRODUCTION Recording and reproducing system specifications usually include a value for "speed error". It is one purpose of the present paper to show that speed error is not really of primary interest — rather one is actually interested in "timing error" and "pitch error". Timing error is the amount by which the duration of a reproduced program differs from the duration of the original program; this is of primary interest in broadcasting operations, where very accurate timing is demanded. Pitch error, on the other hand, is the amount by which the pitch of a reproduced program differs from the pitch of the original program. This is of primary interest in recordings of music which are to be spliced together: a small constant pitch error is not easily detected by the average listener, but when a splice juxtaposes sections recorded with different pitch errors, a sudden change of pitch occurs which is very obvious and disturbing. Although either error can be calculated from a complete knowledge of the other, for practical purposes we will consider them as two separate effects.

In practice, the errors of a *given* system are often identical in recording and in reproducing, so that its own errors in recording are canceled out in reproducing. Operationally, this should be considered as a special case, since a record is more usually reproduced on a *different* transport from that used to make the recording. Therefore, when recording is discussed, reproduction on a "perfect" reproducer will be assumed, and vice versa.

In a disc system, the medium moves at exactly the speed of the turntable on which it lies, and the recording cannot change its physical length. Similarly, in a perforated film system, the medium moves at exactly the speed of the sprocket which drives it, and the recording cannot change its length in relation to the perforations. Therefore in these two systems absolute speed is easily and unambiguously determined, and the speed error *does* determine the pitch and timing errors.

It is usually assumed that in a tape system the "tape speed error" similarly determines the "pitch and timing error". This is only approximately true: even though the tape speed be exactly correct, pitch and timing errors of up to about 1 % may occur.

The NAB [1] and DIN [2] standards for studio recorder/reproducers call for speed errors of ±0.2 % or less. In order to meet this specification under all practical conditions it is necessary to use a closed-loop servo system operating from a "control track" recorded on the tape. This is done, in fact, in motion-picture sound systems using tape, in video tape recorders, and in instrumentation tape recorders.

Many of the causes of pitch and timing errors may be avoided or at least minimized if they are recognized by the user. Thus one is usually able to meet the pitch and timing error requirements of practical sound recording systems without resorting to the additional complication and expense of a servo-controlled system.

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1 EXAMPLES OF PITCH AND TIMING ERRORS

Consider a "perfect" recording containing, for example, a 1000 Hz tone, and marker pulses every minute, for a total of one hour. If this record is reproduced, two types of errors commonly occur: these can be demonstrated by using one system with pitch error and no timing error at the end of a given time; and another system with timing error and a constant pitch error. Let us examine these two cases.

a. Figure 1 shows the pitch and timing errors of a reproducer whose pitch error is + 1 % at the start, decreasing linearly through zero error at 50 % of playing time, down to -1 % at the end of the playing time. With the machine functioning as a reproducer, the pitch error would probably be unimportant, since it changes so slowly as to be imperceptible. The timing error will first increase, up to a maximum error of 0.5 % (9 s at 30 min, for a one hour total recording); then it will decrease; and at the end of the program there will be no timing error at all.

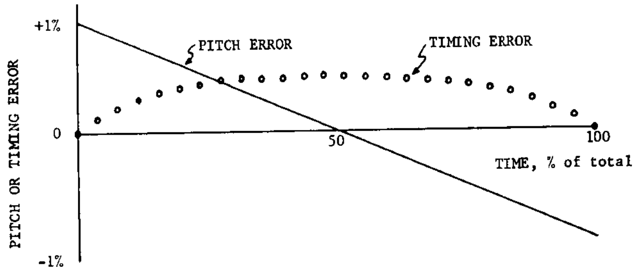

Fig. 1. Pitch and timing error vs time for a system whose pitch error starts at +1 % and falls to -1 % at the end.

If a recording were made with this system, and sections from the beginning and the end of the recording were spliced together, a 2 % jump in pitch would occur — this would be very noticeable. Thus, such a system might be either very satisfactory or completely unsatisfactory, depending on the application.

b. Figure 2 shows the pitch and timing error of a system with a constant + 1 % pitch error. For use as a reproducer, the pitch error would again probably be unimportant, as it is constant. The timing error in seconds will be proportional to the program length — for a one hour program, the error would be 1 % in 60 minutes, or 36 s — an unacceptable amount in most broadcasting situations.

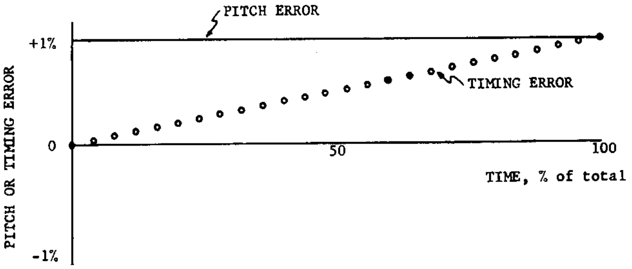

Fig. 2. Pitch and timing error vs time for a system with a constant pitch error of + 1 %.

If a recording were made with this equipment, and sections from the beginning and end were spliced together, no *change* in pitch error would occur. (If this tape were spliced together with one from another recorder which had no pitch error, a change would of course be heard.) Again, this system might be either very satisfactory or completely unsatisfactory, depending on the application.

2 THE SIGNIFICANCE OF TAPE SPEED (THE IDEALIZED CASE)

First consider some idealizing assumptions about tape. They are usually taken for granted, but it will be shown later that they are not really valid. The assumptions are:

1. The tape is infinitesimally thin compared to the capstan radius, so that the capstan peripheral speed and the tape speed are identical so long as the friction between capstan and tape are high enough that no slipping occurs between capstan and tape.

2. The tape is of unvarying length, i.e., is unchanged by tape tension, relative humidity, and temperature; and has no residual stress. Therefore the reproduced wavelength always equals the recorded wavelength.

2.1 Calculation of Tape Speed (Idealized)

Under the above assumptions, the tape speed may be calculated from measurements of the capstan radius r, in meters, and the angular speed Ω, in radians per second ($\Omega = 2\pi N$, where N is the speed in rev/s): s (in m/s) = Ωr.

Both r and Ω are subject to many practical errors: for instance, Ω may change with line frequency when a synchronous motor[1] is used; with line voltage when an induction motor is used; and with temperature and tape tension when the motor is compliantly coupled to the capstan by a belt, rubber tire, puck wheel, etc. Since both speed and radius may be measured accurately and unambiguously, and since they are highly variable depending on the design of the particular tape transport, they will not be further discussed here.

2.2 Measurement of Tape Speed (Idealized)

Under the conditions assumed above, there are several equally valid methods for measuring the tape speed:

Pulley speed and radius.

1. Measure the shaft speed and radius of the capstan itself, and calculate $s = \Omega r$.

2. Measure the shaft speed and radius of an *auxiliary* measuring pulley driven by the tape (this might be the "reel idler", etc.), and again calculate $s = \Omega r$.

Visual determination of the recorded wavelength. Record two pulses a known time T apart, "develop" the pulses [4] so that their position can be seen and measure the length L between them; calculate the speed from $s = L/T$.

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[1] Professional tape recorders often use synchronous motors which run at a speed determined exactly by the power line frequency. A question arises in this case: is the speed error due to power-line frequency errors to be attributed to the tape transport, or to the power line? NAB [1] and IEC [3] standards specify that measurements be made relative to the power-line frequency. Such a choice is rather arbitrary, but must be made one way or the other. In this case, if measurements are made using a commercial power source, timing and counting devices referred to absolute time must not be used, but rather devices referred to the power-line frequency such as strobotachometers, frequency-ratio meters, frequency counters which derive their time-base from the power line, etc. The power-line frequency commonly varies ±0.05 %, which cannot be neglected in comparison to the NAB speed tolerance of ±0.2 %.

Measurement of frequency or time in reproduction of a known recording.

1. Reproduce a test tape containing a recording of known wavelength λ; measure the reproduced frequency f; calculate speed from $s = f\lambda$.

2. Reproduce a test tape containing a recording of pulses with a known length L between them; measure the reproduced time T; calculate speed from $s = L / T$.

Under the assumptions made, the measuring method may be chosen purely in terms of convenience of measuring apparatus at hand. It will be shown later that under real conditions each of these measuring methods has its faults and limitations.

2.3 Pitch and Timing Error from Speed Error (Idealized)

Continuing with these same assumptions, it can be said that the incoming frequency f_{in} , is transformed to a recorded wavelength λ_{rec} according to $\lambda_{rec} = s_{rec}/f_{in}$, where s_{rec} is the tape speed in recording. Inversely, the wavelength in reproducing λ_{rep} , (which equals λ_{rec}) is transformed back into a reproduced frequency $f_{rep} = s_{rep}/\lambda_{rec}$.

Similarly, an incoming time interval T_{in} is transformed to a recorded tape length L_{rec} according to $L_{rec} = s_{rec} \cdot T_{in}$; and $T_{rep} = L_{rec} / s_{rep}$.

Thus one needs only know the error of the recording and reproducing speed throughout the program length in order to calculate the pitch and timing error:

The pitch error at any instant is equal in magnitude to the speed error at that instant. For reproducing, the sign is the same (that is, high speed gives high pitch); for recording the sign is reversed (high speed gives low pitch).

The timing error for any given interval of time may be found by integrating the speed error vs time over that interval. In recording, the sign is the same (high speed gives long program time); in reproducing, the sign is reversed (high speed gives short program time).

3 THE INSIGNIFICANCE OF TAPE SPEED (THE REAL CASE)

The assumptions of the previous sections — that tape thickness is negligible, and tape length is unvarying — are quite necessary in order to relate "tape speed" alone to pitch and timing error. A discussion of the real case, however, will show that the tape thickness is significant, so that the "capstan speed and radius" alone do not determine the tape speed; that, since the tape changes length with tension, and the tape tension changes along its path through the transport, the "tape speed" observed depends on the location along the tape path at which "speed" is measured; and, finally, because of this change of length with tension, plus changes with temperature, humidity, and manufacturing and winding stress, that the reproduced wavelength does not necessarily equal the recorded wavelength, and even a *valid* knowledge of the tape speed does not determine the pitch and timing errors!

3.1 Calculation of Tape Speed at the Capstan (Real)

The relationship "tape speed = capstan surface speed" holds only when the tape is infinitesimally thin. Table 1 lists the capstan radii of several commercial tape recorders, and that of the NAB Standard Speed Measuring Pulley; and the relative thickness of 50 µm total thickness ("regular length") tape. Note that in the USA, the "tape thicknesses" of 0.5 mil (13 µm), 1.0 mil (25 µm), and 1.5 mil (38 µm), etc., refer to the tape *base material only*. Since this specification has no meaning in calculating the tape speed, the *overall thickness* is always used in this paper. Since the tape thickness is in the order of 1 % of the shaft radius, and we are concerned with speed tolerances of 0.2 % for studio recording, a correction factor is obviously necessary, and the driving of the tape by the capstan must be considered as the complicated rolling process that it really is.

The "effective radius" is approximately to the centerline of the tape; therefore the shaft radius must be *decreased* by approximately one-half of the tape thickness, which is to say that the shaft diameter must be decreased by approximately one tape thickness.

The exact factor depends on whether the coating is more or less compliant than the base; the frictional forces between tape, capstan, and capstan idler; which side of the tape (coating or backing) contacts the capstan; and several other factors which are difficult to analyze accurately. Therefore about the only practical method of determining the tape speed for small capstans is to actually measure the tape speed with a pulley whose diameter is great enough to approximate the "infinitesimally thin tape" condition. The NAB pulley, which is compensated for the tape thickness, is usually satisfactory, though larger pulleys are sometimes used. The diameter of the small capstan is then modified according to this measurement in order to achieve the correct tape speed.

One finds experimentally that the speed of the tape corresponds to a point nearer to 38 % (rather than 50 %) into the

TABLE 1 . Transports, capstan diameters, and relative thickness of 50 µm (regular) tape.

	Speed		Nominal Capstan Diameter	Relative Thickness of 50 µm (Regular) Tape = Speed Error If Not Compensated For
Transport Type	mm/s	in/s	mm	%
Ampex 350	95 / 190	3.75 / 7.5	3	1.7
Ampex 350	190/380	7.5 / 15	6	0.8
Ampex 300	190 / 380	7.5 / 15	12	0.4
NAB Speed-Measuring Pulley	any		36	0.14

depth of the tape, so that the correct capstan size is more closely the calculated diameter less 0.76 times the tape thickness. This results in the sizes shown in Table 2 for capstans run by “direct drive” synchronous motors on 60 Hz power lines.

TABLE 2. Capstan sizes used by Ampex for models 350 and 300, for 60 Hz power-line frequency (5, 10 and 20 rev/s), compensated for 50 µm (regular) tape thickness.

Nominal Capstan Diameter, mm	Specified Capstan Diameter	
	mm	inches
3	2.992... 2.997	0.1178...0.1180
6	6.022... 6.033	0.2371...0.2375
12	12.073...12.080	0.4753...0.4756
36 (NAB Speed Measuring Pulley)	36.335...36.340	1.4305...1.4307

This, unfortunately, is not the end of the matter. If a capstan is corrected for regular (50 µm) tape, the double (25 µm) tape does not run the correct speed. As long as one always uses the same capstan diameter, there is no error of pitch or timing; but if different capstan diameters are used, a pitch and timing error appears.

Table 3 shows the actual speed errors which occur when 35 µm (double) and 25 µm (triple) tapes are played on the various capstans which have been corrected for 50 µm (regular) tape. The speed errors are seen to be from 0.12 to 0.67 %.

TABLE 3. Relative speed errors when capstan is compensated for 50 µm tape, but plays 25 or 35 µm tapes.

Nominal Capstan Diameter, mm	Speed Error in % With Given Tape Thickness		
	50 µm (regular)	35 µm (extra)	25 µm (double)
3	0.0	–0.47	–0.67
6	0.0	–0.23	–0.33
12	0.0	–0.12	–0.17

Table 4 shows the relative speed errors when the thin tapes are recorded with one capstan diameter and reproduced with another; errors of 0.11 to 0.5 % result.

TABLE 4. Relative speed errors when tape is recorded with one capstan diameter and reproduced with another capstan diameter.

Nominal Capstan Diameters, mm	Speed Error in % With Given Tape Thickness		
	50 µm (regular)	35 µm (extra)	25 µm (double)
3 and 6	0.0	0.24	0.34
6 and l2	0.0	0.11	0.16
3 and 12	0.0	0.35	0.50

The only solution to these problems is to avoid them: when pitch and timing error are important, either use the thickness of tape for which the capstan was compensated, or else always use the same capstan size. The NAB Standard, in Annex A, “Methods of Tape Speed Measurement”, specifies that speed measurements be made with tape having an overall thickness of 48±5 µm (regular).

3.2 Measurement of Tape Speed (Real)

In section 2.2 we described two direct methods for measuring tape speed — by calculation of speed from $s = \Omega r$ of the driving capstan, or of an auxiliary pulley.

However, in section 3.1 we have shown that one cannot directly measure the effective radius exactly when the tape thickness is significant in comparison to the pulley (capstan) diameter. Thus one is led to measure speed with an auxiliary pulley which may be made large enough to allow an accurate determination of its effective radius. Another practical reason for using the auxiliary pulley is that the tape may slip at the capstan if the tape holdback tension is too great for the capstan idler force and the friction between the tape and the capstan and capstan idler. The capstan speed might be correct but the tape speed wrong: the auxiliary pulley detects this error due to tape slip at the capstan.

But even the auxiliary pulley may give erroneous readings if the pulley is located at the incorrect position in the tape path, because at any instant the speed of the tape changes as the tape goes through the transport. This is due to the elasticity of the tape: the length of a section of tape depends on the strain per unit tension on the tape (a property of the tape materials), and the tension to which it is subjected. Figure 3 shows an example of tensions: the supply tension T_s , of a constant torque machine (say the Ampex 350, on “small reel”) is 0.7 N at the beginning of the reel; the tension at the constant-speed capstan, T_c, has increased to 0.84 N, due to the friction of the tape on the heads in the head assembly. The takeup tension T_t is completely independent because of the constant-speed capstan, and is 2.1 N at the beginning of a reel. The strain per unit force for 6.3 mm (¼ in) tape is about 0.1 %/N to 0.3 %/N (see Appendix); we will use the value of 0.1 %/N (typical for 50 µm regular tapes) in the following examples. The errors could therefore be three times those shown if 25 µm (double) tape were used.

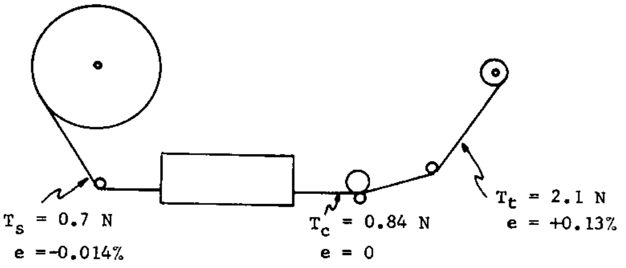

Fig. 3 Tape speed error e for different positions in a transport, with a fixed position in the reel. Tension values are for 6.3 mm tape width.

The tension at the supply reel is 0.14 N less than that at the capstan; therefore the speed at the supply reel is actually 0.014 % slower than that at the capstan; similarly, the tension at the takeup reel is 1.3 N greater than that at the capstan, and the speed is 0.13 % faster than that at the capstan.

This is explained by the fact that the mass of tape flowing by each point per unit time must be the same as that flowing by any other point; otherwise tape would be “piled up” in the system. Therefore the speed must increase proportionately when the tape is stretched more, and decrease when the tape is stretched less. Thus, even though the speed at the capstan incoming side remains exactly constant, the speed at the reel idler will be 0.014 to 0.04 % slower than the speed at the capstan; and the speed at the takeup reel will be from 0.13 % greater to 0.18 % less than the speed at the capstan. Thin tapes would further increase this error by some three times.

Thus it can be seen that the actual tape speed at the takeup reel may differ from the true speed at the capstan by 0.2 to 0.5 % depending on the tape thickness. Therefore the NAB Standard specifies that the speed measurement is to be made *at a position between the head assembly and the capstan,* because this speed is very nearly the same as the speed at the recording and reproducing heads.

For a tension ratio across the head assembly of 1.2 (typical of the Ampex Model 350) the speed at the reel idler is nearly identical to the speed at the capstan. If a higher friction is present at the head assembly due to more wrap of the tape around the heads and guides, or due to a greater number of heads or guides, the speed at the reel idler may be enough lower than the speed at the capstan to suggest that the reel idler should not be used as the position for the speed-measuring pulley.

It should be emphasized again that this section discusses a problem in *measuring* the tape speed: the *indicated* speed would be in error, even though the *actual* speed at the capstan might be exactly correct. It should also be recalled that nothing has been said about the pitch or timing errors.

3.3 Changes of Wavelength between Recording and Reproducing (Real)

For “tape speed” alone to control pitch and timing errors, the reproduced wavelength must equal the recorded wavelength. In practice, the length of a section of the tape — and therefore the wavelength — varies with the characteristics of the tape (strain per unit force, temperature and humidity coefficients of expansion, and viscoelastic properties), and with the way it is used (tape tensions generated by the transport; temperature and humidity environment in use and storage; and tensions, times, and temperatures of storage of the tape both in the tape manufacturing and in the storage of a finished tape on a reel). To the extent that the wavelength changes from the time of recording to the time of reproducing, tape speed errors and pitch and timing errors may be independent of each other.

Effect of tape tension. In section 3.2 we showed that, due to tape elasticity, the speed of a short section of tape changes as it passes through the transport, since the tensions change with position in the transport, but are assumed constant at a given position during the time it takes this short section to pass through the transport.

Now consider the effect of the tape elasticity on the wavelength, due to the change of tension (and therefore wavelength) that occurs at any given point in the transport — for instance, at the head assembly — as the tape is played and one goes from a full supply reel to an empty supply reel.

When a “constant torque supply system” is used (e.g., the Ampex Models 300 and 350), the range of holdback tensions which occurs (including the effect of friction at the heads) is shown in Table 5. The resulting wavelength changes are also shown.

Incorrect tensions (as exemplified by the “small/large” example in the table) can greatly increase the wavelength changes; a similar effect occurs when the holdback tension is incorrectly set, or the stopping brake drags in the Play mode. This also shows that a *standard* tape tension is required for all transports if a standard speed is to give uniform pitch and timing.

If the tape speed remains constant at the heads, which is the case for a direct-drive synchronous capstan motor with proper capstan-idler force, the “pitch change” from beginning to end of the supply reel would be the same as the wavelength change: 0.17 % for the 180 × 60 mm (small) reels, and 0.13 % for the 270 × 110 mm (large) reels, with 50 µm (regular) tape. Use of 25 µm (double) tape will double these errors. Incorrect tensions also may increase the error, with a 1 % error occurring with the “small reel–high torque” condition and 25 µm (double) tape.

This pitch change of 0.1 % to 1.0 % occurs in a transport whose only “imperfection” is the lack of a constant-tension holdback system: the *speed* at the heads is constant here. But as one progresses from the beginning to the end of a reel of tape, the pitch of a recorded tape will change. If the same tape is played without any editing on the machine on which it was recorded, this error is completely compensating, and no error will be seen in the pitch or timing. If, on the other hand, one section of tape is taken from the beginning of a reel, and edited to the end, etc., or if the recording is transferred to a different-size reel, or a different location on the reel, the pitch and timing errors will be apparent.

The use of constant holdback tension eliminates this particular problem completely. There are several commercial audio recorders which do incorporate constant-tension holdback systems.

Effect of Temperature Change. Published values for the temperature coefficient of linear expansion for tape base materials

TABLE 5. Changes in tape tension and resulting change in wavelength at the heads due to change of holdback tension in a “constant torque” transport with 6.3 mm (¼ in) tape.

		Reel Size and “Reel Size Switch” Setting		
		Small/Small[1]	Small/Large[2]	Large/Large[3]
Tension at heads for given position in supply reel	Full	0.8 N	1.6 N	1.2 N
	Middle	1.2 N	2.4 N	1.5 N
	Empty	2..5 N	5.0 N	2.5 N
Change in tension at heads, from full to empty supply reel		1.7 N	3.4 N	1.3 N
Change in wavelength at the heads, from full to empty supply reel				
With 50 µm (regular) tape		0.17 %	0.34 %	0.13 %
For a range of tapes		0.14 to 0.5 %	0.28 to 1.0 %	0.1 to 0.4 %

[1] Small reels, 180 × 60 mm (7 × 2.3 in.); on “small reel” position, torque 0.06 N·m .

[2] Small reels, 180 × 60 mm; on “large reel” position, torque = 0.12 N·m.

[3] Large reels, 270 × 110 mm (10.5 × 4.5 in.); on “large reel” position, torque = 0.12 N·m.

are: $54 \times 10^{-6}/\,{}^{0}\text{C}$ for acetate and $17 \times 10^{-6}/\,{}^{0}\text{C}$ for polyester [5]. Thus, if the temperature changed from 20 to 35 ^{0}C (68 to 95 ^{0}F), the change in recorded wavelength (and therefore the pitch and timing errors) would be 0.08 % for acetate base and 0.025 % for polyester.

Effect of Humidity Change. Published values for the hygroscopic (humidity) coefficient of linear expansion for tape base materials are 150×10^{-6} / % RH for acetate, and 6×10^{-6} / % RH for polyester. Thus, if the humidity changed from 30 to 70 %, the change in recorded wavelength (and therefore pitch and timing errors) would be 0.6 % for acetate base, 0.024 % for polyester.

Effect of Viscoelastic Characteristics. It is a well-known fact [6] that the base materials used for magnetic tape are "viscoelastic": that is, when subjected to a stress, there is an elastic strain which takes place immediately and an additional viscoelastic strain that continues as long as the stress is applied. When the stress is removed, the elastic strain is immediately recovered, but the viscoelastic strain takes a long time to recover. These effects are dependent not only on the base material, but also on the temperature: higher temperatures accelerate the rate of viscous strain.

Two problems are of concern here:

1. When the base material is manufactured, a "residual stress" is left in the material. Du Pont literature for Mylar [5] shows a residual strain of 0.5 % at a 100 °C temperature. (This temperature could occur during storage and shipment, although the plastic reels would show obvious damage from this temperature.) Even under lesser temperatures, the stress tends to relieve itself, although more slowly. When the tape is dried in an oven after coating, part of this stress is relieved. Specifications are not published on commercial tapes, and this data is somewhat difficult to measure accurately. Preliminary tests were performed by the Ampex Magnetic Tape Laboratory on tapes purchased on the open market: a sample's length was measured; it was left in a 60 °C environment for 8 hours, then returned to room temperature and measured again. In six samples of polyester-based tapes, shrinkages of 0.008 %, 0.07 %, 0.03 %, and 1.7 % were measured, and two samples showed an *expansion* of 0.02 % and 1.7 %! One can only guess that the history of the samples was different, and that this was the major factor.

2. After the tape is wound on a reel under tension — by the manufacturer or by a user — viscoelastic elongation also occurs until the stress is relieved. This very complicated problem has been reported on by Tramposch [7, 8]. The tape manufacturer usually winds the tape under a rather high tension to minimize the chance that the tape pack will lose its tension — and consequent "firmness" — during shipment. (When this does happen, the shock received in shipment may ruin the reel of tape.) Suppose that the user makes a recording on a new reel of tape which has this built-in residual stress; when he winds the tape on a reel at a *lower* tension than that used by the tape manufacturer, the tape will shrink, and the wavelength will change. It is possible that this was the cause of the 1.7 % shrinkage reported in the previous paragraph — we really don't know as yet exactly how much pitch and timing error can occur from this cause.

3.4 Pitch and Timing Error (Real)

In section 2.3 we discussed the calculation of pitch and timing errors in the idealized case from a knowledge of the tape speed only. In section 3.1, the discussion of the calculation of the real tape speed at the capstan shows possible speed errors of up to 2 % that might be overlooked. But section 3.3 shows that changes in tape tension, temperature, humidity, and viscoelastic elongation all cause the wavelength to change between recording and reproducing, and this causes a corresponding pitch and timing error which adds to the errors from speed alone.

Thus it is possible to calculate the real pitch and timing errors (other than those from viscoelastic elongation) if sufficient care is taken. In general, however, it is more practical simply to measure errors of an actual system.

4 PRACTICAL MEASUREMENT TECHNIQUES AND PROBLEMS

If a measurement accuracy of about ±1 % is adequate, one may consider that speed, timing, and pitch errors are synonymous, and use any of the measurement techniques outlined in section 2.2, on the measurement of speed for the idealized case.

If accurate measurements are required, one must measure speed, timing, and pitch errors separately, being careful to define exactly the system being measured: some errors are due to the transport alone (e.g., wrong capstan speed; tape slip at the capstan); some are due to the tape alone (e.g., changes due to temperature, humidity, and the relief of manufacturing stresses); and some are due to the tape-and-transport interaction (e.g., tape thickness and capstan diameter; tape elasticity and transport tensions; tape elongation due to winding stresses left by transport, and viscoelastic properties of the tape).

4.1 Speed Error Measurement

Speed, timing, and pitch errors must all be referred eventually to the tape speed at a specified tape tension. The tape speed may be measured with 50 µm (regular) tape, by a correctly designed pulley[2] placed between the head assembly and the capstan. The measurement should be made at least at the start, middle, and end of the supply reel, and the greatest error reported.

Direct speed measurement has the advantage of not requiring a special test tape; also, tape length variations due to tension, temperature, and humidity variations, and residual stress and viscoelastic elongation are eliminated. The disadvantage is that correct tape speed does not guarantee correct pitch and timing, for exactly these reasons.

4.2 Pitch Error Measurement

The pitch error of a reproducer may be measured directly by reproducing a test tape containing a recording made at a known tension with a known frequency (i.e., at known speed of known wavelength). As with the speed error measurement, the pitch error measurement must be made at the start, middle, and end of the supply reel, and the greatest error reported.

The error of the reproduced frequency may be measured by one of the following methods:

1. Frequency is measured relative to the power-line frequency (as specified in the NAB Standard [1] and IEC Standard [3]) by a frequency meter which uses the power line as a time-base reference, e.g., the Hewlett-Packard Electronic Counter Model 5211 A. The pitch error in percent is then $e = 100\,(f_{rep} - f,_{rec})/f_{rec}$. Any convenient frequency may be used; 1000 Hz would be especially convenient, because the error then reads directly: the

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[2] A pulley suitable for this measurement is manufactured by Dubbings Electronics, Copiague, New York. The diameter should be checked, as earlier models did not include the tape thickness correction; the dimension should be that shown in Table 2 .

last place of a four-place counter is parts-per-mil (tenths of a percent). Many frequency counters have a crystal oscillator for an “absolute” time base, but can also be connected to read frequency *ratio* instead. If we then let R_{rec} represent the ratio of the frequency recorded on the “perfect” test tape to the power-line frequency in recording, and R_{rep} the ratio of the frequency reproduced to the power line frequency in reproduction, the error in percent is: $e = 100\ (R_{rep} - R_{rec})/R_{rec}$.

2. Frequency error is measured by the “drift” meter of a flutter and drift meter, such as the Micom Model 8100; the Woelke (Gotham Audio) Model ME 101 or 102, or the EMT Model 420. The frequency on the test tape must correspond to that for which the flutter meter is designed: 3000 Hz has been the standard frequency used in the USA; the “Preferred Frequency” [9] of 3150 Hz is used in Germany, and in the German-made flutter meters (EMT and Woelke (Gotham Audio) and has been proposed for use in the USA. All of these meters have internal oscillators with a frequency accuracy of better than ±0.1 % which is used to set the “zero” point of the drift meter. Therefore, unfortunately, none of these meters takes line-frequency errors into account, but rather charges them to the tape plus transport system.

3. Time is measured for a $2\ \pi$ radian phase shift (i.e., 360°, one full cycle) of the reproduced frequency. (This method is especially convenient when the specialized equipment for methods 1 and 2 is not available, because only an ordinary oscilloscope with line synchronization is needed.) The frequency is most conveniently that of the power line used, i.e., 50 Hz or 60 Hz. When the oscilloscope is synchronized to the power line, the wave reproduced from the test tape will appear to drift forward or backward with time, depending on whether the pitch is high or low. The pitch error may be calculated as the ratio of the period of the recorded signal (i.e., the time for one cycle), to the time t that it takes for one cycle of the reproduced wave to drift by due to pitch error. Since the period T is the reciprocal of the frequency, when the power-line (which is the recorded signal) frequency is 50 Hz, $T = 20$ ms; for 60 Hz, $T = 16.7$ ms. Therefore the error in percent is $e = 100\ T / t$.

For 50 Hz, e (in percent) $= 2/t$, for 60 Hz, e (in percent) $= 1.7/t$. For the NAB and DIN specifications of “speed” error, ±0.2 %, the time for one cycle to pass the reference point must be at least 10 s for a 50 Hz line, or 8.5 s for a 60 Hz line. This method is most convenient with systems which have less than about 2 % error: otherwise the measuring time for one cycle is less than 1 s, and accurate measurement of the time with a stopwatch becomes impractical.

These methods all measure the pitch error directly. The inherent disadvantage is the need for an accurate test tape. “Accurate” includes not only the accuracy of recording in the first place (recording speed, tension, and frequency), but also the errors due to the length-changing effects of the tape. In other words, the “tape plus transport” *system* is measured. If special care is not taken, one may falsely conclude that the transport has pitch error, when in fact the test tape is at fault.

Thus far, no accurate pitch error test tape is known. Acetate tapes have too high a coefficient of expansion with humidity, and some polyester tapes have too high a residual stress and viscoelastic flow. A completely stress-relieved polyester is being investigated, in hopes that it may be satisfactory for such a test tape. The question of viscoelastic changes due to stress relief while the tape is wound on the reel also still remains unanswered.

The Ampex Flutter Test Tapes contain an approximately 3 kHz tone which is sometimes used for pitch error measurements. It should be pointed out that only the *flutter* on this tape is closely controlled, as its purpose is flutter measurement. Because of the residual stress problem with polyester bases, the flutter test tapes are made on acetate base, which has a high humidity coefficient of expansion; therefore these tapes are not suitable for precision pitch error measurements. Since this is the case, neither the input frequency, the speed, nor the tension is accurately controlled in making these tapes: the wavelength may be in error by as much as ±0.4 %, in addition to the error due to humidity changes.

If a suitable material could be found for the tape base, then it would be desirable and possible to control accurately the wavelength in manufacturing flutter test tapes; then they could be used for pitch error measurements also. In the meanwhile, these flutter test tapes should not be used for *precision* pitch error measurements.

4.3 Timing Error Measurement

The timing error of a reproducer may be measured directly by reproducing a test tape containing a recording having a known time interval when recorded at a known tape tension and speed. The same problems with changes in tape length occur as in the pitch error measurement described above. As discussed before, the timing error measurement will depend on the reel sizes, length of program, etc. Therefore a particular measurement is valid only for a particular condition: “a 30 minute program, 540 m of 50 µm tape on a 180 × 60 mm reel, at 190.5 mm/s, reproduced with a timing error of ± __ s.” (“A thirty minute program, 1200 ft. of 2 mil tape on a 7 × 2.3 in reel, at 7.5 in/s reproduced with a timing error of ± __ s.”)

5 TRANSPORT MAINTENANCE PROBLEMS

Speed, pitch, and timing errors in a professional audio recorder/reproducer which was correctly designed to begin with can usually be traced to one or more of the following problems:

1. Wrong capstan speed in “indirect” (rubber-tired) drives. Test for this problem by measuring the capstan speed with a stroboscope sticker on the capstan. Check at the beginning, middle, and end of a full reel of tape. Adjust as required, per the instruction book.

2. Tape slips at the capstan. This can be caused by a dirty or polished capstan[3]; by low capstan idler force (wrong adjustment — too loose); by capstan idler solenoid not “bottoming” (wrong adjustment — too tight); or by a holdback tension which is too high — see below.

3. Incorrect tape tension. This may be caused by incorrect adjustment of the resistors which set the tension; by excessively high or low line voltage; by dragging of a “stopping” brake — usually due to incorrect brake solenoid adjustment; by an incorrectly set “reel size” switch; or, on a constant-tension system such as the MR-70, due to a failure in the constant-tension system.

Problems similar to these can of course occur in any type of tape transport.

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[3] Revised 1999: This originally said “This can be caused by a dirty capstan or capstan idler”. But the capstan idler should not drive the back of the tape – it should only press the tape against the capstan. So a dirty idler would not cause the tape to slip on the capstan.

6 CONCLUSIONS

The NAB Standard calls for a maximum tape speed error of ±0.2 %. The NAB speed measuring procedure must be followed carefully if speed measuring errors larger than this tolerance are to be avoided.

This “speed error” tolerance should not be interpreted as guaranteeing that the pitch or timing error will also be better than ± 0.2 %, since speed measurement alone does not take into account pitch and timing errors due to tape length and tension changes. A standard tape tension would need to be established if “speed” were to be meaningful. This tension would probably be per unit tape width, and might even be different for different tape thicknesses.

In the case of a practical problem with either pitch or timing, one must be careful to measure the actual system and phenomenon of concern, under the actual conditions which prevail. As mentioned at the beginning of this paper, a system may be perfectly satisfactory for one usage but unsatisfactory for another. With the information in this paper, one should be able to choose the important factors and ignore the irrelevant ones.

APPENDIX

Tape Strain per Unit Force

An elastic material placed in tension will stretch. The relative elongation, $\Delta l/l$, is called the strain, ε. The strain per unit force, ε/F, may be measured directly for a given length of tape or it may be calculated from the formula $\varepsilon/F = 1/AY$, where A is the cross-sectional area of the tape, and Y is the Young’s (stretch) modulus of the tape. The Young’s modulus is a bulk property of the material; the values for the commonly-used tape base materials are given in Table Al, taken from the base manufacturer’s specifications.

TABLE Al. Young’s modulus of common tape base materials.

Material	Young’s Modulus of Base, GN/m^2	Young’s Modulus of Coated Tapes, GN/m^2
Cellulose acetate	2.3	1.9...3.1
Polyester	3.8	2.1...3.6
Polyester, tensilized	5.5	3.2...5.6

Actually, the Young’s modulus of the tape coating itself may be considerably greater or less than that of the base material, so that the Y modulus of the base alone is of very limited value. The effective Y modulus range for **coated** tapes is given by Krones [10], and these values are also shown in Table Al.

Because of this wide spread of effective Y modulus values, it is more satisfactory to consider directly the measured values of strain per unit force (ε/F) than to try to calculate values from the cross-sectional area and the Y modulus. Krones tabulates the values for strain for a 10 N load for 40 European and USA tapes, with acetate, polyester, tensilized polyester, and polyvinylchloride bases. Table A2 is taken from Krones’ summary.

TABLE A2. Strain per unit force for manufactured 6.3 mm (¼ in) wide tapes.

mm × µm	Length Designation	ε/F, % /N		
		minimum	average	maximum
6.3 × 50	regular	0.08	0.10	0.14
6.3 × 35	extra	0.12	0.16	0.23
6.3 × 25	double	0.10	0.18	0.30

Thus, for 6.3 × 50 (regular) tapes, a good value is 0.1 %/N (1 N = 3.6 oz). The 6.3 × 25 (double) and 12 µm (quadruple) tapes, and narrower tapes (3.8 mm tapes used in cassettes), would have still higher ε/F values.

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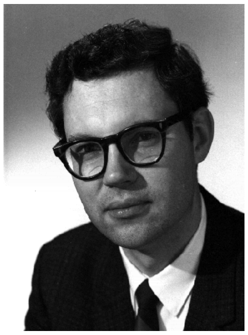

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