Design Improvements for Motion Picture Film Projectors

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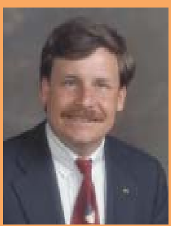

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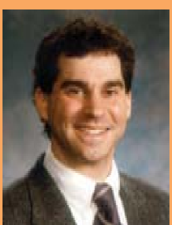

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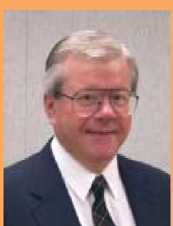

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With all the recent hype about digital cinema, it is all too easy to forget that there are still only a handful of high quality D-Cinema systems in operation throughout the world, compared with the hundreds of thousands of conventional cinemas which are still using and which will continue to use 35mm film for many years to come. The 35mm film projector in use today is little changed from its counterpart of forty years ago, simply because the basic mechanisms work well and give little trouble. Unfortunately, this very reliability has had the negative effect that in recent years very little research and development has been done on ways in which the standard 35mm projector might be improved. This paper, which resulted from work instigated by Kodak Research Labs, describes how the previous lack of research in this area is being put right, and highlights some fascinating new developments that could prolong the useful life of opto-mechanical film projection long into the era where digital cinema might otherwise have been expected to take over.

This paper describes design improvements developed for motion picture film projectors that are intended to improve the quality of the overall screen image. In particular, new designs for the intermittent, or Geneva mechanism, and for a "Universal" lamp house are described. These improved designs allow the system light efficiency and uniformity to be improved, resulting in significant increases in screen luminance.

Motion picture film projectors have been successfully used in theatres for decades to project high-quality images with broad audience satisfaction. Indeed, relative to qualitative parameters such as image resolution, color reproduction, contrast range, and the elusive "film look", motion picture film has provided image quality generally unmatched by electronic projection systems. On the other hand, the film experience has been degraded by a multitude of factors, including the film release print process, image unsteadiness, film buckle or flutter, poor illumination, dye fade and wear, and physical artifacts such as scratches and dirt. Aside from the development and popularization of very large screen film formats (such as 70 mm) and the associated projection equipment, the industry has made very few design changes to film projectors which actually improve the on screen image quality. Indeed, the state-of-the-art motion picture film projector[1] has changed very little from those produced in the 1950s when robust color films and xenon arc lamps were introduced. Granted, projected image quality has been significantly enhanced over the years by progressive improvements in the design and manufacturing of the projection lenses. However, many of the basic mechanisms within film projectors, including the intermittent film drive, the shutter, and the illumination system or lamp house, are relatively unchanged since the 1930s. Thus, there continue to be opportunities to make design improvements to the classic opto-mechanical motion picture film projector, which could, in turn, improve the projected image quality.

It is well known that a significant percentage of the commercial theatres fail to meet SMPTE 196M standard which specifies 35 mm film projection at 16 (±2) fL luminance at screen center, with a nominal 20% fall off to the corners. Indeed, it is commonplace for commercial theaters to only provide 6-10 fL luminance at screen center, with 30-50% fall-offs to the corners. Although much of this performance difference can be attributed directly to cost cutting by the exhibitors, deficiencies in projector design relative to light efficiency (and ease of use) also contribute to this slippage. Design improvements related to light delivery in a film projector can provide both direct benefits to the screen illumination,[2] but also indirect benefits related to alignment and robustness, ease of use, and image quality. As the light efficiency in a traditional motion picture film projector is largely determined by the operation of the intermittent film drive and the design of the lamp house, design changes in these areas offer the greatest potential for an economical, quality improvement.

The Geneva Mechanism

Geneva mechanisms are widely used in motion picture film projectors to intermittently advance the film through a film gate having a projection aperture. The film is moved or advanced by a Geneva mechanism until an image frame is in alignment with the projection aperture. The film is then held stationary for a discrete period during which light is passed through the aperture, film frame, projection lens, and onto a screen. This intermittent frame-by-frame motion of the film is enabled by the Geneva mechanism shown in Fig. 1, which consists of a continuously rotating driver and an intermittently rotating

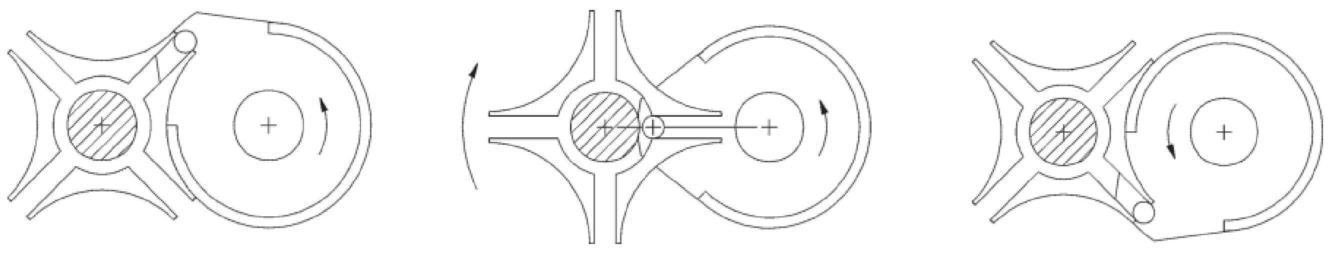
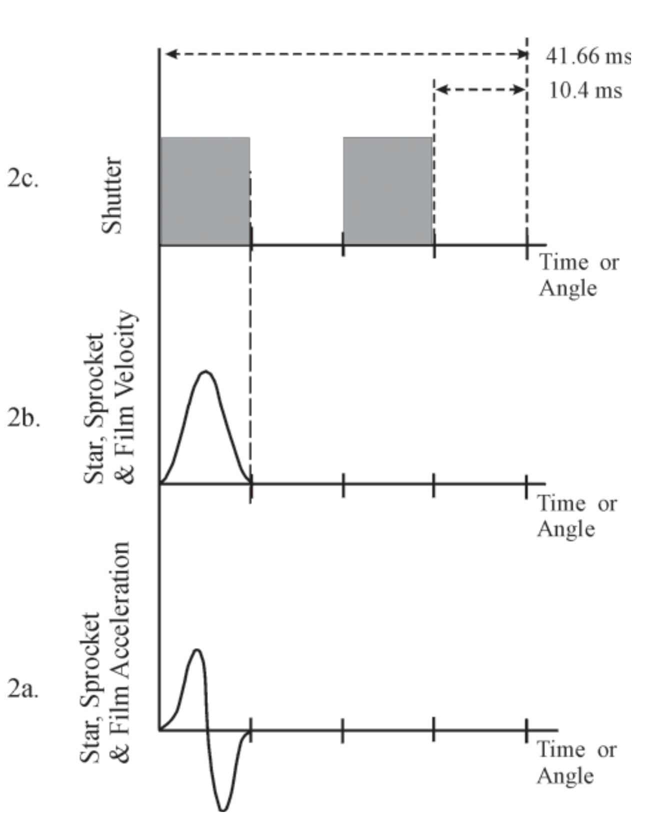


Fig. 1: Standard Geneva Mechanism and motion throgh index

star wheel. In a motion picture projector the star wheel shares its central shaft with a sprocket, the teeth of which are engaged with perforations in the film. Therefore, when the driver moves the star wheel, both the star wheel and the film experience a resulting intermittent motion. Motion picture film is typically projected at a rate of 24 fps, such that a new film frame is positioned in the projection aperture every 1/24 second, or~42 ms. The standard projector Geneva mechanism moves a film frame into the projection aperture with an indexing time of ~1/4 of the frame period, or ~10.5 ms. As shown in Fig. 2a, the star at first experiences a slow acceleration, followed by a rapid increase to a peak acceleration, and then a sudden reversal to peak deceleration, after which acceleration gradually tapers off. As a result, the star, sprocket, and film are slow to get going, with minimal displacement for the first ~15 degrees of driver rotation, and thus only gradually reach peak velocity, before slowing down during the deceleration phase. The timing relationships of the star movement and shutter operation are shown in Figs. 2b and 2c. During essentially all of this indexing time, the shutter blocks the light incident to the film and prevents the appearance of "travel ghost". The projectable frame time, which would appear to be 3/4 of the total frame period, is further reduced to only 1/2 of the total frame period, as the typical projector employs a two-bladed shutter to provide two blanking periods per frame, thus boosting the apparent frame rate to 48 fps, and thereby reducing the flicker perceived by the human eye. Furthermore, it is necessary for these two shutter intervals to be equal in duration in order to limit perceived flicker. Therefore, because one blanking period must be 1/4 of the frame time in order to blank the projected image as the film moves, the other blanking period must be of essentially the same duration.

Fig 2. : Timing diagram for a standard Geneva mechanism



The star wheel is the key element in enabling the Geneva mechanism to convert uniform rotary motion to incremental rotary motion. Traditionally, the projector star wheel has four radially extending straight slots spaced equally around the periphery of the star. Interposed between these slots are concave cam guide surfaces, which, like the slots, are uniformly dimensioned and arranged. A driver, comprising a restraining cam, a drive arm, and a drive pin near the far end of the drive arm, is employed for indexing the star wheel. The restraining cam has a side cam surface, which is convex, and configured to interact with the concave cam guide surfaces of the star wheel. The close contact of this convex cam surface to the concave cam guide surfaces restrains the star wheel from experiencing rotary motion except during the periods in which the star wheel is driven by the drive pin. The star wheel is thus restrained intermittently, and in a manner such that the straight slots sequentially receive the drive pin. Thus, in the conventional projector intermittent, each 360° revolution of the driver produces 90° of rotation of the star wheel and attached sprocket. Correspondingly, a standard two-bladed shutter utilizes a pair of opposing blades each providing beam blockage over 90° of its own rotation.

As can be seen, if the indexing time of the Geneva mechanism could be reduced, the shutter blanking periods could, in turn, be shortened, thereby increasing the available screen light visible within a frame. Most simply, the indexing time might be reduced by using a star wheel which has only three straight slots. In that case, engagement of the star wheel with the driver pin occurs over only 60° of the 360° revolution of the driver, thus providing an indexing time of ~7 ms per frame to move a film frame into the projecting aperture. While a 3-slot star wheel would thus decrease the indexing time (and thereby increase the available projection time), the acceleration forces applied to the drive pin, slots, and the load (the film and film perforations) are greatly increased over those of a 4-slot Geneva, making the 3-slot mechanism undesirable for use in a projector. While the drive pin can be shaped[3] to modify the acceleration profile and reduce the forces on the drive pin, a 3-slot Geneva mechanism would still be prone to failure in a motion picture projector application.

A variety of alternate designs for the enhanced intermittent film drive mechanisms have been considered,[4] the most successful of which was the "Powers" movement.[5] In the case of the "Powers" movement, the star wheel employs four round pins, which engage with a cam that has a single, large diamond shaped cam driver. While this intermittent reduces the indexing time to ~1/5 of a rotation of the cam, by supplying prolonged periods of uniform controlled peak acceleration to the star, a high sliding velocity may introduce unsteadiness and gradual pin wear. This likely prevented the widespread adoption of this mechanism.

A New Geneva Mechanism

A new Geneva mechanism for use in motion picture film projection has been developed[6] and demonstrated. As opposed to the traditional mechanism, which uses a star wheel with straight slots, the star wheel of the new design employs slots with curved surface profiles. It has been shown that with the appropriate shaping of the slot walls, the velocity profile encountered by the star wheel can be modified to reduce the indexing time, while maintaining control over the acceleration and load forces experienced by the film and the drive mechanism itself. As shown in Fig. 3, the slot walls of the star wheel have a concave portion adjacent to the mouth of the slot, followed by a slight convex portion in the middle of the slot, and a straight portion innermost in the slot. The details of the design of the slot shape can be adjusted to control the steepness of the ascent to peak acceleration, the transition into mid index (the zero acceleration point), and the acceleration profiles between these two extremes. At operating speeds, the drive pin enters a slot and rides along the concave, convex, and straight portions of the first wall, and then exits the slot by riding along the surfaces of the opposing wall in reverse order. Unlike the conventional projector Geneva mechanism, the drive pin does not fit the star wheel slots, except in their deepest portions. As a result, the new Geneva can experience some chatter at very low speeds, as the drive pin separates from the wall. However, at normal operating speeds, with the inertial torque many times greater than the drag torque on the film, the drive pin will remain in contact with the appropriate wall of the slot, and the mechanism will function without losing control of the driven load.

To illustrate the design concept more fully, a timing diagram (Fig. 4) shows the relationship of the acceleration and velocity of the star wheel to the pin load and the shutter operation during the first half of a frame time. Basically, the curved slots are shaped to produce a prolonged period of high acceleration prior to mid index and a similar prolonged period of deceleration after mid index, after which the deceleration is rapidly reduced to zero. Comparison of the timing diagram for the standard Geneva mechanism (Fig. 2) and the improved Geneva mechanism (Fig. 4), shows that the acceleration and velocity motion profiles are shorter and more abrupt at the beginning and end of index. While in the conventional Geneva, the drive pin is engaged with the slot over 90° of rotation, the drive pin of the new mechanism enters the shaped slot later and leaves earlier, effectively engaging over a lesser angle. As the star wheel undergoes a smooth and continuous motion through mid index, the pin load (Fig. 4c) remains under control, thus minimizing both the applied forces and the wear experienced by both the mechanism and the load (the film). As the design concept specifies deliberate shaping of the slot walls, which have a relatively large surface area, wear on the mechanism is minimized as compared to alternate approaches involving shaped or high load drive pins.

Within limits, the new Geneva mechanism, or "Quickermittent", is amenable to a wide range of potential designs utilizing different slot profiles to provide different peak accelerations, pin loads, and indexing times. A variety of designs have been modeled and tested, including a device that has nearly an identical indexing time to that of the conventional mechanism, but has reduced peak acceleration and peak pin loads (50% and 55% respectively), for reduced forces and wear on the mechanism and on the film. Alternately, an increased peak acceleration and peak pin load can be traded off for reduced indexing times, which is, of course, the intended goal. One such design utilized shaped slots that provided a dramatically reduced indexing time (64% or 6.7 ms) with increased peak acceleration and pin load (142% and 106% respectively) compared to the conventional Geneva. Thus, this version of the "Quickermittent" completes its indexing over only 56° of rotation of the driving cam, compared to 90° for the standard mechanism and

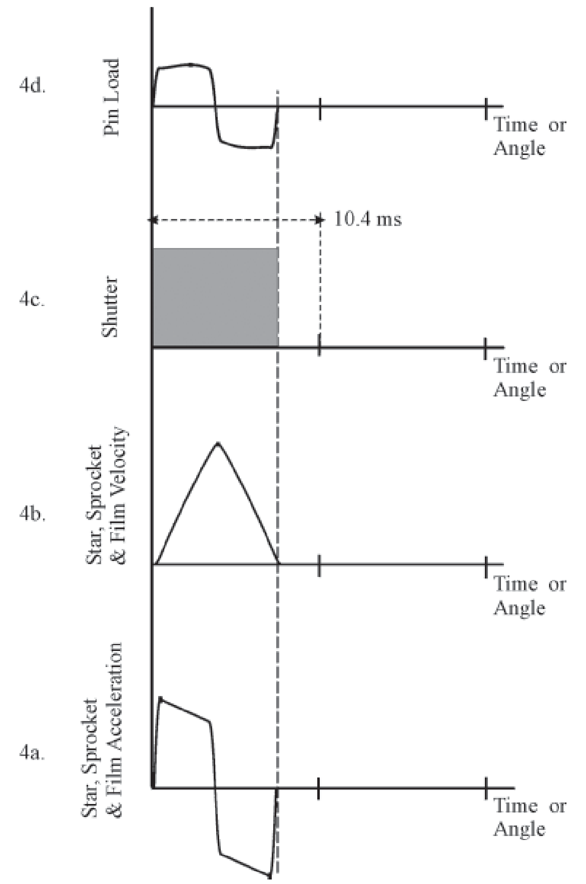


Fig 4. : Timing diagram for the new Geneva mechanism

Fig 3. : The new Geneva mechanism

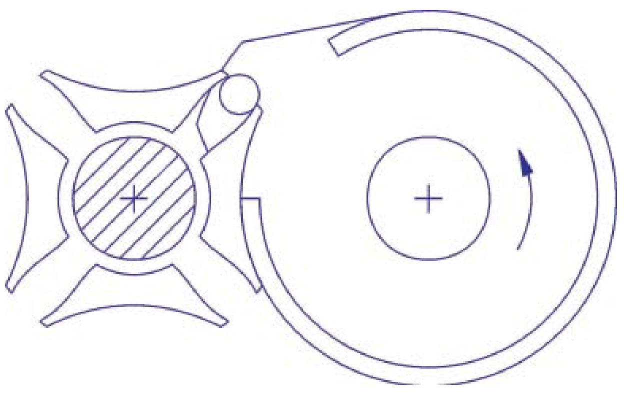


Fig 5. : The standard star wheel, the driving cam and the new star wheel

provides 36% more screen light during a frame time. A third, less aggressive design, which has also been evaluated, provided reduced indexing times (73% or 7.7 ms or 66° rotation) and ~27% more screen light, with peak acceleration and peak pin loads comparable to the conventional Geneva (100.6% and 91% respectively). As shown in the timing diagram of Fig. 4d, each of the shutter blades will be closed for less time than in the conventional projector, and the perceived screen luminance will be proportionally increased during each frame. Of course, the actual light gain achieved on screen will be reduced somewhat relative to the design and tuning of the shutter to minimize "travel ghost", which is the visual perception of the moving film.

Thus far, "Quickermittent" Geneva mechanisms have been successfully prototyped and tested in Christie, Simplex, and Century projectors, using hardware appropriately adapted for each system. Figure 5 illustrates the "Quickermittent" star wheel, with its curved slots, along with the standard star wheel and cam. When it is designed to work with the same cam driver, a new star wheel is actually slightly smaller than the standard star wheel. In general, a "Quickermittent" can be retrofit into an existing projector, using the modified star wheel and a conventional or slightly modified cam driver, and with little or no change to the remainder of the projection head. Gate tension may be slightly higher in a projector modified with a "Quickermittent", in order to provide sufficient film drag to maintain control over the film and to prevent film or mechanism damage. Preliminary tests also have indicated that the "Quickermittent" tends to be somewhat noisier than the conventional mechanism, but the increased noise levels are likely acceptable, and can be minimized with proper adjustment and design. Before widespread adoption by the projector manufacturers and exhibitors, extensive field trials and design optimization are likely required to validate and improve the performance of the "Quickermittent".

The Projector Lamp House

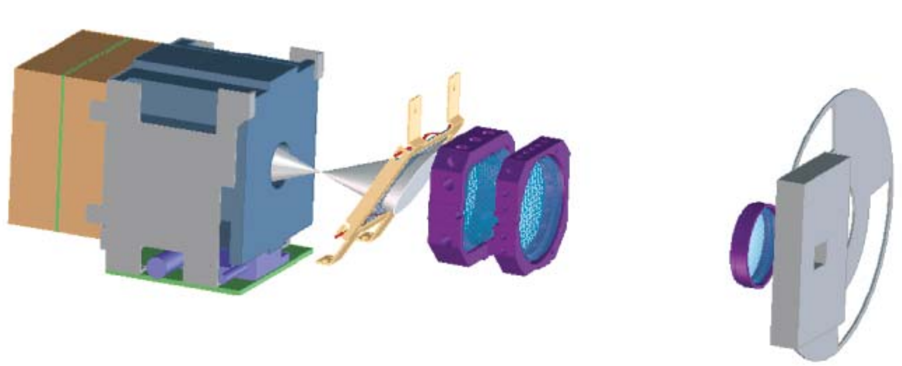
The successful development of a lamp house useful for motion picture film projection appears to have been one of the first great illumination design problems of the industrial age. Many of the classical illumination optical designs, from the Köhler system,[7] to the fly's eye illuminator,[8] and the elliptical reflector were either conceived of, or enhanced, in order to project film images. Generally, the conventional lamp house used in motion picture film projectors consists of a short arc xenon arc lamp inset within a deep-dish elliptical mirror. Compared to the numerous alternatives, many of which involve combinations of reflectors and lens elements, the basic lamp house, with its single circularly symmetrical elliptical reflector, is notable for its simplicity and low cost. However, as the typical lamp house overfills the rectangular film aperture with a large round beam of light, this system is quite inefficient. Moreover, alignment of these lamp houses, whether of the xenon arc to the first focus of the ellipse, or of the reflector and lamp to the projection aperture and lens, has proven sufficiently difficult and time consuming in that the effort overwhelms many theaters. Although, over the years, various opportunities have been available for improvement in lamp house design, many of the efforts to date were directed to small adjustments in the design of the elliptical reflectors and coatings, or to debates over whether to utilize horizontally or vertically installed xenon arc lamps.

The "Universal" Lamp House

A new lamp house has been designed and prototyped, with the objective of improving the light efficiency and uniformity of the light delivery to the screen, as well as improving the robustness and ease of alignment. In particular, the new lamp house was designed utilizing a fly's eye optical illumination system working in combination with modern xenon arc lamp modules. The fly's eye optical system, which uses lenslet arrays to reshape and homogenize the light beam, was originally developed by Zeiss Ikon[8] in the 1940s. This design approach, which was later adapted to work in combination with the short arc xenon lamp,[9] was considered difficult to use because of alignment issues with respect to its "waffle" lens. In all likelihood, the widespread adoption of a fly's eye design in cinematic projection was limited by the cost and difficulty of manufacturing the required lenslet arrays. However, in recent decades, light homogenizing illumination systems employing either a fly's eye design or kaleidoscope optics have been extensively developed for the photolithography industry. More recently, such designs have been successfully applied in the design of electronic projection systems, using xenon, metal halide, and other arc sources. Furthermore, when such systems are properly designed and implemented, the optical alignment is actually less sensitive to misalignment as compared to the equipment used in conventional systems.

As shown in Fig. 6, the new lamp house employs a series of condensing lens elements and two lenslet arrays in a classical fly's eye optical system between the lamp and the film gate. The first condensing lens after the lamp is used to fill the first lenslet array with a specular beam. The first lenslet array, which is constructed of spherical lenses with rectangular apertures, breaks this beam into a

Fig 6. : Optical layout with the 'Universal' lamp house



series of beamlets that are coupled to the corresponding lenslets of the second array. The second lenslet array, working in combination with a relay lens, images the lenslets of the first array onto the film gate in overlapping fashion, thus providing a rectangular area of uniform illumination. A field lens, located near the film gate, is used to image the second lenslet array into the entrance pupil of the projection lens. As compared to the fly's eye designs of prior years,[8,9], this system not only benefits from modern manufacturing methods for producing lenslet arrays, but also utilizes modern light sources. In particular, the prototype "Universal" lamp houses are designed to accept either the Cermax™ EX-1500-F and EX-2400-F short arc xenon lamps, but also the MVDR 1.5 kW, MVDR 1.9 kW, and MVDR 3.0 kW Illumination Modules. These lamp sources, which provide brighter (low etendue) beams than the traditional short arc xenon bulb lamp and elliptical reflector combination, are available from Perkin-Elmer Inc. of Asuza, CA.

The Cermax™ lamps are integrated lamp packages, in which the electrodes, rare gases, and arc are contained in an integrated package with datum features. As these lamps operate with smaller arc gaps compared to bulb lamps of the same wattage, the arc plasma is smaller, and the light source is effectively brighter. By comparison, the MVDR modules combine conventional short arc xenon bulb lamps with compound reflectors, to synthesize a brighter effective source by capturing some light with the secondary reflector. This light is then recycled back through the bulb and primary reflector. These modular lamp sources, which are for example used in the Roadie™ series electronic projectors offered by Christie Digital Inc., are relatively rugged and provide external datum features for easy repeatable installation. Within these modules, conventional bulb xenon arc lamps are pre-aligned to the compound reflectors, prior to installation in a projector. Ushio Inc. also manufacturers a version of the modular lamp source with compound reflector. In combination, with the use of brightness enhanced xenon sources and a fly's eye system, which channels light through a rectangular aperture, significantly brighter illumination is provided as compared to the conventional system. For example, a prototype lamp house, constructed as described, demonstrated a ~35% light gain and 16 fL center screen luminance through a 'scope aperture when projected on a 30 ft screen with a 114 ft throw while using a 1500 W lamp. Screen luminance data should soon be available for the "Universal" lamp house equipped with 2.4 kW and 3.0 kW lamp sources.

The lamp house system of Fig. 6 also provides several secondary advantages. In addition to the added light efficiency, the screen illumination has improved uniformity, with typically only a 10-15% gradual roll off from center to corners. In practice, the efficiency and uniformity improvements delivered to the screen luminance by the "Universal" lamp house are dependent on the choice of projection lens used with a given system. The process of light homogenization also has the secondary advantage of desensitizing the illumination to flicker from arc and gas turbulence within the lamp. Furthermore, the fly's eye type design desensitizes the illumination to horizontal or vertical misalignment of the lamps, as shifts of ~1.0 mm will cause minimal change in the illumination uniformity. These tolerances easily fall within the repeatability of alignment provided by the datum features of either the Cermax™ or the modular lamp sources, thus providing simple, safe, and repeatable lamp placement. Additionally, the prototype system uses a Calflex™ C infrared filter from Unaxis Optics Inc., providing superior IR rejection and a natural color temperature of 5500 K. Finally, the illumination system can be optionally configured[10] to suppress the visibility of scratches and dust on the film with the addition of a holographic or engineered diffuser located in the gate upstream of the film.

A mechanically integrated version of the lamphouse with improved optics has been designed and prototyped. This system, as shown in Figs. 7 and 8, had been designed to be universally modular with Christie, Simplex, and Century projectors with minimal modification required for either the lamp house or the projector heads. The Christie and Simplex projectors need only have some lamp baffling removed, while the Century requires the addition of a lens mount attached to the main casting. This system is compatible with both pedestal and console style mounting, and it accepts either the Cermax™ or modular style lamp sources as well. The opto-mechanics have been designed to provide easy accurate alignment of the lens elements within the projector, and easy integration and alignment of the lamp houses with the projector heads. To ensure robustness under the high thermal loads, the various lens elements are manufactured from Pyrex™ and are mounted with pliant adhesives for low stress. The thermal design within the "Universal" lamp house is engineered to both minimize heat transfer among components and modules and to quickly remove heat from the various assemblies. Furthermore, the "Universal" lamp house was designed for easy mechanical access from both the sides and top, with kinematic features to ensure alignment during servicing. Finally, the "Universal" lamp house, with approximate dimensions of 28.5 in. x 15.0 in. x 14.1 in. (LxWxH), is significantly smaller than most pedestal or console mounted lamp houses used in projection systems today.

Theater Application

The "Quickermittent" and "Universal" lamp house have been tested in combination, and provided over 20 fL (7500 lumens) center screen luminance on a 'Scope

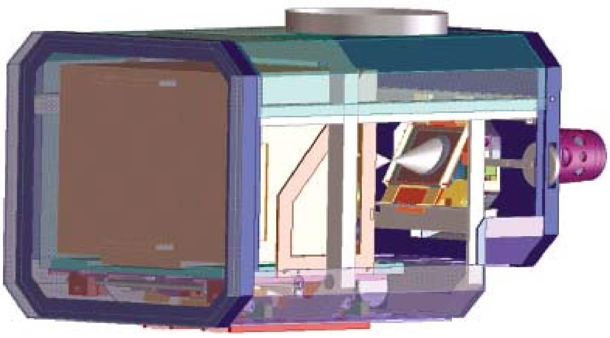
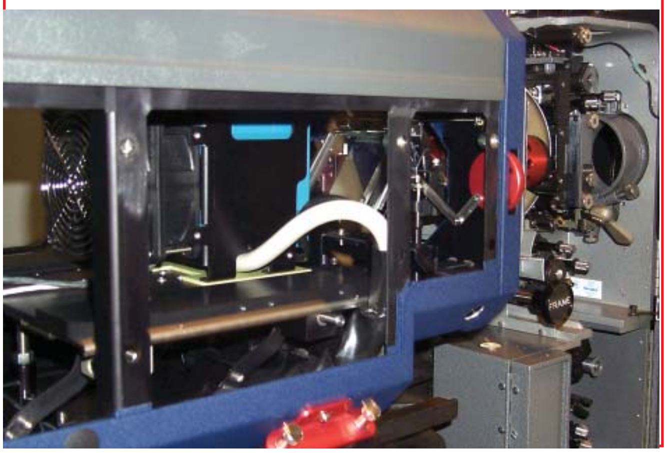


Fig 7. : Mechanical design of the 'Universal' lamp house

Fig 8. : Photograph of the assembled 'Universal' lamp house



aperture 30 ft screen with a 1500 W lamp. Alternately, that is ~70% more light than provided by a projector operating with a standard intermittent and lamp house equipped with a 2 kW lamp (4500 lumens). Projection with the "Flat" or 1.85 projection apertures shows a less dramatic ~40% light gain, as light is lost from clipping by the aperture plate (6500 lumens). Unlike the many proposals for improving screen luminance by altering the basic 35 mm film format, these light gains can be achieved with minimally disruptive upgrades to the existing projection equipment. The light efficiency gains provided by the new intermittent and lamp house designs could simply be used to provide a better screen image. Alternately, this efficiency can be used to light an existing screen with a lower power lamp than used today. This combination has the additional benefit of reducing the thermal load through the film, thereby reducing film buckle and the resulting shifts through focus, and thus improving the image quality. Likewise, the light efficiency gain can also be traded away for a reduction in scratch and dust visibility in the projected image.[10]

Although both the "Quickermittent" and the "Universal" lamp house have been successfully demonstrated and tested, these designs would benefit from field testing and optimization prior to widespread adoption by the industry. Advantageously, both designs lend themselves to being retrofit into existing equipment or into current projector designs with minimal changes required to that equipment. Furthermore, the component and assembly costs for these designs should be generally comparable to the existing equipment it would replace. Certainly, either the Cermax™ or the modular compound lamp sources cost more (as much as 2-3x more) than today's xenon bulb lamps of identical power. While the Cermax™ lamps are simply more costly, the added cost introduced by the modular lamp sources is mainly due to the cost of the modules themselves. However, these modules can be re-lamped (usually by the manufacturer or a specialty vendor) and then re-used by the theater. With the modular lamp sources, one lamp module can be exchanged for another within minutes, without the need to re-align and refocus the bulb within the projector. Admittedly, the "Universal" lamp house could be redesigned to accept light from a conventional bulb lamp and lamp house, however, the advantages relative to performance, size and, ease of use would be lessened. The ultimate question relative to adoption of the "Universal" lamp house, with its modern xenon lamp sources, could be whether the advantages relative to efficiency, ease of use and alignment, and performance outweigh the additional lamp costs for the cash strapped exhibition industry.

Other Opportunities

Although new possibilities have emerged from the development efforts directed to the "Quickermittent" and the "Universal" lamp house, there are other significant opportunities to improve the projected image quality provided by motion picture film projectors. Compared to other effects which degrade the projected image quality, such as scratches, dirt, and film jump and weave, film buckle is the least obvious, but perhaps most significant, contributor to quality loss. Borberg[11] describes both the basic phenomenon of film buckle, as well as one solution involving modulated air blasts to mitigate the effect. While much of the light incident on the film is transmitted through it, and subsequently imaged to the screen by the projection lens, a portion of this light is absorbed, either by the dyes in the case of color film, or by the silver grains in the case of black & white film. The absorbed light heats the film, which being an elastic material, deforms out of plane. This thermally induced deformation can shift the image outside of the designed depth of focus of the projection lens, thereby degrading the on screen image resolution. The standard two-bladed shutter, which is typically located between the lamp source and the film gate, causes the film to be pulse illuminated twice per frame. The film buckles during the first illumination period, relaxes some during the intervening dark period, and then buckles (or deforms) further during the second illumination period. Film buckle can potentially be reduced through either passive or active means, by incorporating the appropriate design changes to the projector. However, these design changes, which need further development, are more invasive to the design of the projector head than either the "Quickermittent" or the "Universal" lamp house. If, however, such changes were adopted and the film buckle accordingly reduced, the projected image quality would be perceptually improved through the present projection lenses provided by ISCO or Schneider, or through any new and improved projection lenses which could be developed.

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