Photoelastic Dynamic Stress Analysis Using Synchronized Strobe Techniques

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Abstract

Dynamic structural analysis is an essential aspect of engineering design; various structural analysis techniques lead to enhanced designs, as well as failure prediction and prevention. Photoelastic stress analysis, a technique based on the concept of material birefringence, is a non-destructive and highly-efficient method of structural analysis with great potential to be used in dynamic analysis. This research explores the possibility through the synchronization of a strobe light and a digital camera. Using this synchronization, it may be possible to capture progressive images of the stress distribution throughout a turbine model rotating at variable and increasing speeds. Utilizing a rapid prototyping technology called stereolithography, the model can be created such that it can be both prepared and analyzed by the method of photoelasticity. With the possibility to make adjustments during the design stage of production comes considerable and valuable cut backs on material waste and production costs. The possibility of using dynamic photoelasticity to analyze stress progression has the potential to create significant efficiency, economical, and environmental benefits in all aspects of engineering and industry.

Keywords: Photoelasticity, Rapid Prototyping, Dynamic Stress Analysis, Turbine

1. Background

The absence of dynamic stress analysis can have catastrophic effects, as was seen in the destruction of the European Space Agency Ariane 5 rocket launcher in 1996. Having suffered a computer failure, the launcher turned uncontrollably. The launcher may have been recovered, but unforeseen and untested aerodynamic forces destroyed the launcher. Had a dynamic stress analysis of possible aerodynamic conditions been performed, this situation could have easily been avoided.

Dynamic structural analysis is an essential aspect of engineering designs, but one that is often difficult to perform. Standard finite element methods can predict areas of failure to a certain degree of accuracy; however, these methods often make assumptions that may not be applicable to a real-life situation. In contrast, performing a dynamic stress analysis of an architectural structural design provides an account of the loading not only during static conditions, but also possible dynamic conditions, such as earthquake vibrations or hurricane-strength winds. Dynamic stress analysis can lead to adjustments during the design stage of production, creating both economical and efficiency benefits for all aspects of engineering. One such method is that of photoelasticity, a non-destructive structural analysis technique. In conjunction with a synchronized stroboscope, it is possible to capture dynamic stress analysis using photoelasticity.

1.1. objective

This research delves into the possibility of capturing photoelastic dynamic stress analysis images through the use of a stroboscrope and digital camera. Specifically, this technique was tested on a model turbine rotating at various steady speeds. A stroboscope, which is a strobe synchronized with periodic motion through a digital signal, is capable of flashing with each complete rotation of a model turbine. This method creates the illusion of a static turbine to the camera, allowing one to capture and collect progressive still frames of the stress progression throughout operation. Inspection of this stress progression provides valuable data about prediction and prevention of failure during dynamic operation.

2. Photoelasticity

Current structural analysis methods, such as finite element and numerical methods, have limited applications when analyzing intricate geometries. As the demand for more intricate part designs increases, so must the efficiency and diversity of structural analysis techniques. Photoelastic stress analysis (photoelasticity) is one such technique, with many economical benefits to engineering design. Photoelasticity, which provides both quantitative and qualitative analysis, allows a loaded model to be analyzed while still in the design stage, which means a design can be adjusted before production. A non-destructive technique, photoelasticity allows the same model to be reused during analysis, again reducing costs. The universality of this method provides for its application to all areas of engineering design, such as analysis of architectural structural designs, prosthetic implants, various engines and airplane landing gear.

Photoelasticity, a method based on material birefringence, is a simple technique, consisting of a number of polarizing plates (polarizers) surrounding the model. A polarizer is a collection of parallel slits, only emitting light components in the direction of the slits. The emerging light is termed ‘polarized light’, and any series of polarizers allows the direction of the polarized light to be controlled. [1] This polarized light is then incident on the object being analyzed, either reflecting or transmitting through the material, depending on the opacity of the material.

Material birefringence is the ability of a material to split incident light into two component rays; this property only exists when the material is stressed. The direction and speed of the propagating light are always coincident with and proportional to the direction and magnitude of the principal stresses, respectively. [2] The light, out of phase as it emerges from the material, passes through an analyzer. At this point, only the components parallel to the axis of the analyzer are transmitted, creating interference patterns. The amount of interference is proportional to the phase difference of the propagating light, and is therefore directly proportional to both the difference in principal stresses and the maximum shear stress. [1]

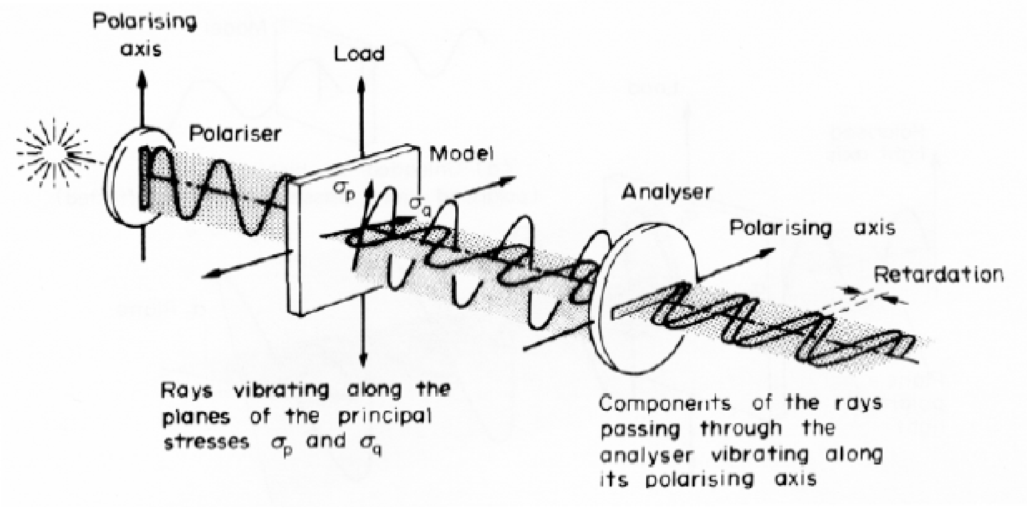

Figure 1 Stressed translucent model in transmission polariscope set-up [3]

The interference patterns, which appear as colorful fringes unique to a specific stress distribution, provide an immediate representation of the shear stress distribution throughout the model. In transmission photoelasticity (in which polarized light passes through a translucent model) this pattern represents the shear stress distribution throughout the entire model. However, in reflective photoelasticity (in which polarized light reflects off of an opaque model) this pattern represents only the shear stress distribution on the model surface.

2.1. Grey Field Polariscope 1000 (GFP)

The Grey Field Polariscope 1000 (GFP 1000) was developed by Stress Photonics, Inc., a Madison, Wisconsin-based company specializing in photoelasticity and thermoelasticity. This polariscope performs reflective photoelasticity, applied to opaque models. The GFP 1000 is capable of producing fringe patterns of very high resolution. At points where the principal stresses are equal in magnitude but opposite in direction, black fringes called isoclinics appear, which can be confused with fringes of zero shear stress, also appearing black. [3]

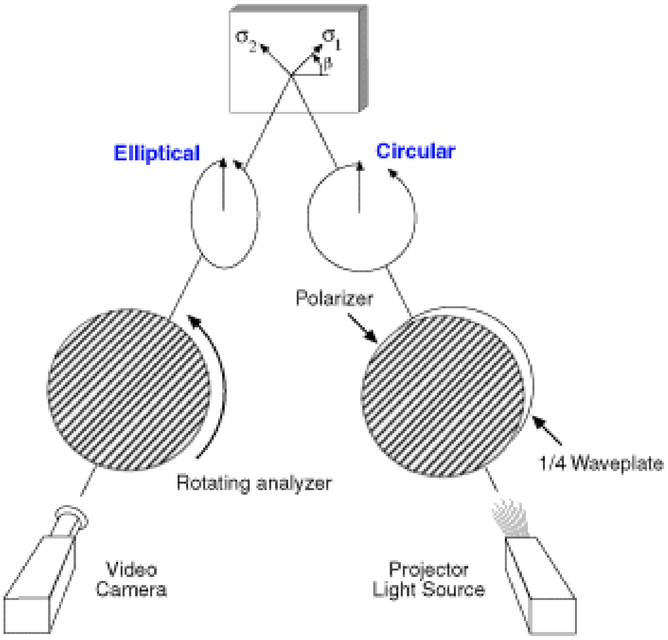

Figure 2 Grey Field Polariscope 1000 setup [4]

The GFP utilizes circularly polarized light, a method in which quarter-wave plates (45° to both the polarizer and analyzer planes) are inserted into the set-up. [4] These quarter-wave plates break the light into two components, equal in magnitude and 90° out of phase. [5] The emerging light is termed “circularly polarized”. This method does not change the interference between the light components, but eliminates all isoclinics. [3] Once the circularly polarized light is incident on the object, the reflected light passes through an elliptical polarizer, which breaks the light into two components, 90° out of phase and of unequal amplitude. [5] The emerging light then passes through the analyzer, producing the colorful interference, or fringe, pattern. The fringe pattern is based on a contrast between the colors blue and red. Areas that are blue represent areas in compression, and areas that are red represent areas in tension. The variation of intensity and shades of the two primary colors represents the difference and strength of the stress magnitude. [1]

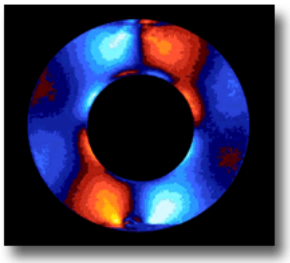

Figure 3 Aluminum ring undergoing diametrical compression, demonstrating the color pattern produced by the GFP [4]

The GFP allows for photoelasticity of opaque, non-birefringent objects through use of a thin, birefringent epoxy coating applied to the outer surface of the model. The coating thickness need not be completely uniform, as the GFP automatically measures and accounts for slight thickness variation. The object itself must have a reflective covering, such that the light can be reflected through the epoxy coating. The strain distribution on the surface of the model is then transmitted to the coating, which in turn is the strain distribution pattern that is visible during analysis. [6] This strain distribution is directly proportional to the stress distribution, so an immediate qualitative stress analysis is available. A quantitative stress analysis is available through the use of Hooke's relations of principal stresses and strains. [7] In order to make this conversion, the Young's Modulus and Poisson's Ratio for the specific birefringent material must be known.

3. Rapid Prototyping

Rapid prototyping is an additive process, as compared to traditional methods of subtractive manufacturing. Rapid prototyping creates models and parts directly from a computer file, creating the three-dimensional object layer by layer. There are various machines able to perform rapid prototyping; one such machine is the stereolithography apparatus (SLA). This machine uses an ultraviolet laser to cure a thin of layer of liquid photopolymer. [8] The laser selectively cures the liquid photopolymer into successive cross-sections (on the order of 0.002 to 0.008 inches thick) of a three-dimensional object, which is built on a platform descending in a vat of the liquid polymer. [9]

One particularly interesting aspect of this liquid polymer is that it is a birefringent material. This material property eliminates the need to apply the epoxy coating to a part created on the SLA, therefore making photoelasticity one step easier. The object still needs to be coated with a reflective paint; however, the reflective coating is applied to the inside of the object, in order to prevent light from transmitting through the object without being reflected.

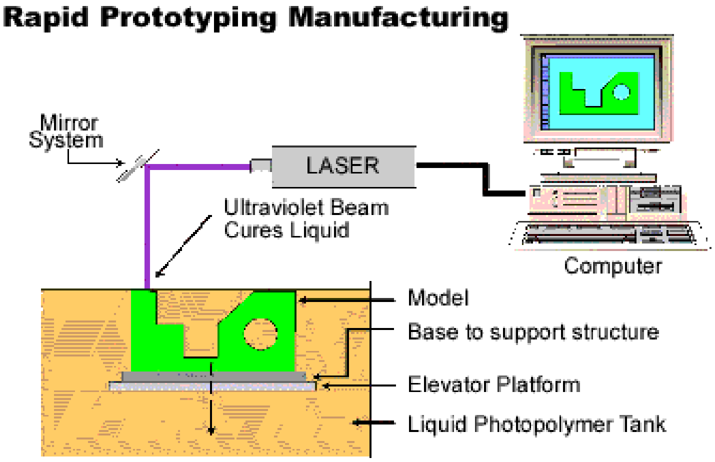

Figure 4 Schematic of Stereolithography Apparatus (SLA) [8]

Photoelasticity, a highly efficient stress analysis, is complemented by rapid prototyping . Rapid prototyping can be used to create models of extremely complex geometry; models not achievable using traditional prototyping methods. Photoelasticity is a straight-forward and accurate method of analyzing these complex parts under loading. In addition, the quantitative stress values found using photoelasticity are proportional to the Young's Modulus of the birefringent material used. Due to this proportionality, there exists a direct correlation between rapid prototyping material and production materials.

4. Testing

In order to test photoelasticity using a stroboscope, a model turbine, created on the SLA and attached to a three speed box fan motor, was analyzed using the GFP 1000 located at Stress Photonics, Inc. The stroboscope was automatically synchronized with the motor such that flashed once per revolution. This analysis includes recording a still image of the turbine rotating at various speeds.

4.1. birefringence test

The efficiency of this photoelasticity method of stress analysis depends entirely on the material birefringence of the SLA liquid photopolymer. Therefore, it was essential that this particular material property was tested and confirmed before photoelasticity was performed. In order to test the birefringence, a simple experiment was set up, analyzing a disk (0.1 inch thickness, 1.5 inch diameter) created on the SLA. The disk was placed into a C-clamp, and a uniaxial compressive force was applied. The loaded disk was then placed between quarter-wave polarizers, creating a simple transmissive polariscope. When polarized light (in this case, produced by a white computer screen) passed through the polariscope, the presence of birefringence was immediately visible to the naked eye, evident as a colorful fringe pattern.

4.2. turbine model design

A turbine is essentially an elaborate fan, and it is subjected to extremely hot exhaust in various engines. In particular, this experiment was carried out on a modified model of a turbojet turbine, based on designs by the National Aeronautical and Space Administration (NASA) [10], as well as turbine blades designed at Georgia Institute of Technology. [11] The design, created using Solidworks software, was altered to provide the best analysis; the model has only five blades, much less than an actual turbine would possess. This is for visual purposes, as photoelasticity is an analysis based almost entirely on visualization. The blades, at 2.15 inches, are also much longer in proportion to the hub (3 inch diameter) than those on an actual turbine, again for visualization purposes.

Each blade also possesses fourteen cooling holes, each with a diameter of 0.05 inches. The cooling holes on the model serve a dual purpose; in addition to contributing to the accuracy of the model, the holes provide a guaranteed stress concentrator on the model. These stress concentrators assure that areas of high stresses exist around the holes, marking areas which were of particular interest during the photoelastic stress analysis.

Another area of great interest is the junction between each blade and the hub underside. Fillets were added to the attachment point on the outer hub, for added strength. The hub design had to be modified to account for an attachment apparatus between the hub and the motor. This attachment involved a simple 0.25 inch screw, reinforced washer, and hex bolt. However, the attachment needed to be designed such that the model can be physically reversed for analysis of the underside attachment point.

4.3. model preparation

In order to execute photoelasticity on the model, some preparation was necessary. The model is hollow for a good reason; because the analysis uses the actual SLA material as the birefringent material, the insides of the blades and hub were coated with reflective aluminum paint. The GFP 1000 is specifically calibrated to a coating of Krylon^{TM} Dull Aluminum Metallic Paint. Each blade hollow was spray painted at close range with that particular type of paint. The layered surface of the part, due to the method with which the SLA builds, prevented the paint from uniformly coating the insides of each blade. These visible layers decreased the accuracy of the photoelastic analysis.

A reflective coating was needed on the underside of any hub area that was analyzed. Since underside of the attachment points between the blades and the hub was analyzed, it was necessary to paint the outside of the hub. This area was spray painted as uniformly as possible to maximize design balance.

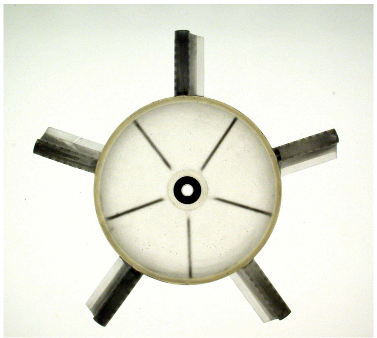

Figure 5 Photograph of model completely prepared for reflective photoelasticity

4.4. experiment methodology

The photoelasticity experiment was carried out utilizing the GFP 1000 located at the facilities of Stress Photonics, Inc. The light source was consistent flashes from a stroboscope, synchronized with the rotation of the turbine model by a LED illuminator-sensor. One blade was marked as a calibration point, indicating to the LED illuminator-sensor when one rotation has been completed. The camera was synchronized to the stroboscope, but only recorded images when controlled. A slower shutter speed was used in order to ensure that the entire strobe flash duration was captured; therefore a necessary recovery time was available to the camera. The still images captured were then collected and compared, revealing the stress progression on the model surface during dynamic operation.

The turbine model rotation was controlled via a modified three-speed box fan motor. Photoelasticity was performed as the model was static, rotating at the lowest speed, and rotating at the highest speed. The speeds recorded for conventional use of the box fan, while close to the actual speeds during experimentation, were no longer accurate due to the model exchange. When switching from the commercial plastic fan to the SLA model turbine, material weight, as well as dimensions, will change the output rotational speed of the motor. The speeds were measured using the stroboscope, which receives a digital signal from the turbine rotation speed and provides the most accurate values for rotational speed of the model turbine. The aerodynamics of the model changed the rotation speeds depending on the model orientation. When mounted with the original configuration, the lowest speed was 1230 rpm, and the highest speed was 1416 rpm. When the model attachment was reversed, the lowest speed was 1452 rpm, and the highest speed was 1554 rpm.

As previously stated, specific areas of the model were analyzed. These areas included the lower blade surface (particularly the cooling holes) and the underside of a blade/hub attachment point Three experiments were executed, examining different model areas: one lower blade surface at various speeds, one hub/blade attachment point at various speeds, and a residual stress experiment of five static blades containing flaws, including cracks and cuts.

5. Results

The first area analyzed was the lower surface of one blade, and images were captured when the blade was both static and rotating at low (1230 rpm) and high (1416 rpm) steady speeds. A comparison of the photoelasticity images did not show significant changes in the stress distributions throughout the experiment. This particular experiment was inconclusive, neither proving nor disproving that dynamic photoelasticity is possible. The lack of changes in the stress progression could be due to the low centripetal forces present in the blade. Another possibility is that the thickness of the blade was not great enough to show drastic color changes, as the level of birefringence is directly proportional to material thickness.

The second experiment analyzed the underside of the blade/hub attachment point, while the area was both static and rotating at low (1452 rpm) and high (1554 rpm) steady speeds. A notable stress progression is visible in a comparison of the photoelasticity images captured as the speed was increased. The stress progression visibly becomes more compressive as the rotation speed increases, denoted by a decrease of the red fringe area. A comparison of the graphical representations obtained from the images (data collected along the white arrow path) further confirms the increased compressive stress distribution, particularly toward the inner hub area.

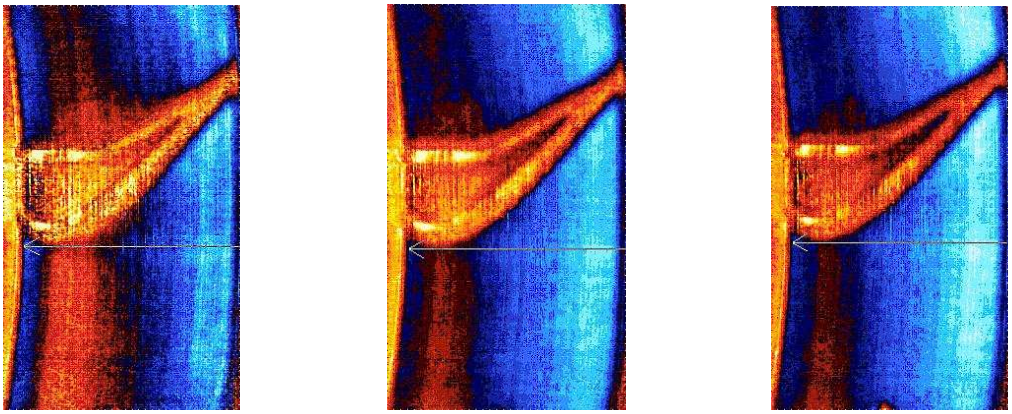

Figure 6 Still images of the stress progression on the surface of the model (blade attachment point) as it is (a) static, (b) rotating at 1452 rpm, and (c) rotating at 1554 rpm

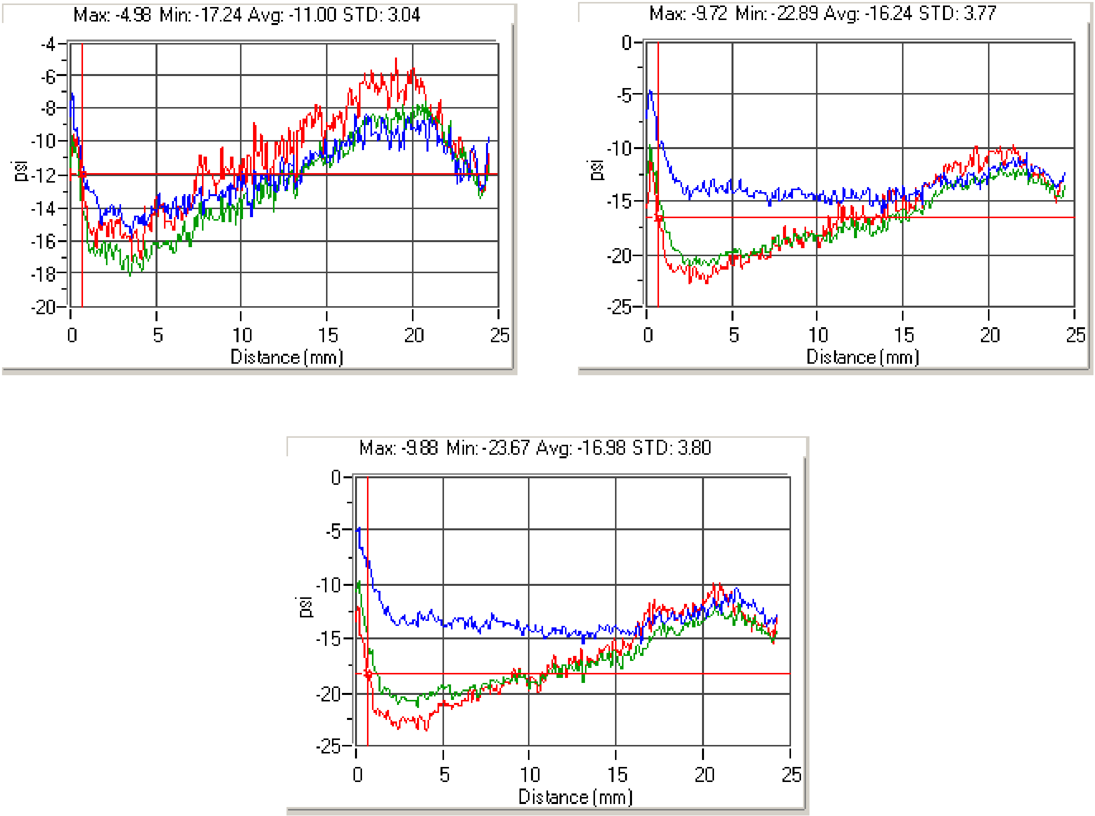

Figure 7 Graphical representations of the stress progression on the surface of the model (blade attachment point) as it is (a) static, (b) rotating at 1452 rpm, and (c) rotating at 1554 rpm

The images display areas of white vertical lines, particularly visible across the outline of the blade. These white lines are the result of the build layers affecting the photoelastic analysis, possibly by distorting the polarized light or preventing the reflective coating from penetrating the thin layers. Further sanding of the part may lead to a reduction in these visible layers in the dynamic photoelastic analysis.

The residual stress experiments yielded interesting results, displaying the predictable nature of cracks to propagate into areas of high stress concentrations. Although beyond the scope of this research, this set of experiments suggests an interesting topic of further research.

6. Conclusions

Although not entirely conclusive, this research completes the first step in proving that dynamic photoelasticity is a possible method of accurate dynamic stress analysis. Further confirmation could be made by analyzing a model undergoing more significant stress distribution changes. However, the slight stress progressions visible in the results of this research display the potential of dynamic photoelasticity to accurately analyze the dynamic stresses existent on the surface of a model undergoing dynamic operation.

If this technique of capturing dynamic stress progression is proven to be useful, the potential impact on engineering and industry is monumental. Photoelasticity now allows for a non-destructive stress analysis on a wide variety of engineering designs, regardless of size, material, or complexity. In conjunction with rapid prototyping, dynamic photoelasticity is particularly valuable. Not only will better designs arise, but adjustments to existing designs can be made during the designs stage of production, reducing both wasted materials and production costs. Using this method, dynamic stress analyses can be performed throughout the lifetime of a part as maintenance, allowing one to assess wear and fatigue during operation. The possibility of using photoelasticity to visually represent stress progression during dynamic operation has the potential to create significant efficiency, economical, and environmental benefits in all aspects of engineering and industry.

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