Optimization Design and Analysis of All-terrain Vehicle Based on Modal Analysis

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Abstract. Under a certain stiffness and strength, the dynamic characteristics directly affect the stability and off-road quality of the all-terrain vehicle (ATV) when driving on complex terrain. With the innovative design of ATV, the 3D model and the finite element analysis model are established. Based on the static analysis, ANSYS analysis software is applied for the body modal simulation analysis, aiming at reducing the body deformation and improving the low-order natural frequency of ATV. By comparing the influence of the finite element modal analysis results on the dynamic characteristics and stiffness characteristics of the ATV under typical conditions, the weaknesses of the structural design are pointed out, which provides the research basis for the further improvement and technical upgrading of the prototype.

1. Introduction
The all-terrain vehicle has the advantages of strong off-road capability, stability, and wide applicability. It can run smoothly on harsh terrain such as beaches, river beds, forest roads, streams, mountains, and deserts. Observe the development of ATV, it is mainly used in outdoor operations, cross-country sports, transportation tools, public security and fire protection\textsuperscript{[1-2]}.

2. ATV structure and working principle
ATV with superior performance should have good performance in climbing, crossing obstacles, and resisting overturning\textsuperscript{[3]}. According to the requirements, a new ATV was proposed and designed (Fig. 1), which has the following characteristics: 1) The axle is placed on the top of the car body to simplify the structural design of the steering system and suspension system; 2) The two-point body is fixed to avoid body tilt and enhance wheel grip; 3) Mechanical four-wheel steering system reduces the minimum turning radius and improves the driving flexibility of ATV; 4) The shock absorber and the air spring are used together to improve the shock absorption effect and increase the smoothness.

Based on the Solidworks software to design, analyze, evaluate and simplify the model, the key parts such as the frame, cross arm, trailing arm and steering arm are selected from A36 material (Elastic Modulus $E=200GPa$, Density $\rho=7850kg/m^3$, Poisson's Ratio $\mu=0.26$, Yield Strength $\sigma_y=250MPa$), the total weight is about 252kg.
1) When the ATV runs on the horizontal road as Fig.2, it runs smoothly and receives simple force. The suspension, steering system and body bear the least impact, and the stiffness and strength of the components can easily meet the design requirements.

2) When the ATV runs on the off-road road as Fig.3, the wheels on the same axle are not on the same plane. In order to maintain the body stable and avoid rolling, the cross arm is adjusted accordingly with the undulating conditions of the road. At the same time it touches the ground and improves wheel grip. The ATV has stronger off-road capabilities, excellent driving smoothness and stability. However, in this state, the CArms are staggered in opposite directions, the SArms bear alternating loads, and the CArms, TArms, STArms, SArms, Wheels and other components are subjected to complex forces.

3. Static analysis of ATV
ANSYS is used for static analysis of the simplified ATV model, to obtain the stress distribution and deformation under the static load of the extreme turn on the off-road road. Under this condition, the ATV structure had the most complex force, which was enough to verify whether the stiffness and strength design meet the design requirements.

3.1. Model establishment and meshing
A simplified ATV model was established by Solidworks, the wheels were set as rigid bodies, and key parts such as the Frame, Beams, SArms, STArms, TArms and CArms were retained. The ANSYS simulation analysis model can be obtained by using hexahedral mesh[4] (Fig.4).
3.2. Load addition and analysis solution
The applied load $W$ is composed of the body weight $G$, the rated load $Q$ and the inertial force $F_a$ \cite{5} in the vertical direction; the model is running under ideal conditions, and the acceleration in the vertical direction is taken as $a=0.547\,\text{m/s}^2$, $F_a=(m+M)a=236\,\text{N}$, load $W=G+Q+F_a=4556\,\text{N}$. Analyze wheel fixation constraints, turn on the maximum and minimum mark switches, and get stress nephogram and deformation nephogram (Fig.5).

According to the stress nephogram, the maximum stress $115.83\,\text{MPa}$ is on the axle, and the rest stress is mainly distributed on the frame. The maximum stress does not reach the yield strength of A36, which meets its strength requirements. According to the total deformation nephogram, it can be seen that the frame is a weak component \cite{6}, which has a maximum downward bending deformation of $2.43\,\text{mm}$. The short TA arms deform more than the long TA arms, and the stress nephogram and total deformation nephogram are in line with the actual situation.

4. ATV nodal analysis
Modes are the natural vibration characteristics of mechanical mechanisms, and each mode has a specific natural frequency, damping ratio and mode shape. Modal analysis can point out the weak links of the components of the mechanism in the movement process, effectively improve the stiffness characteristics of the structure, and provide a reference for the improvement design of ATV.

4.1. Theoretical basis of modal analysis
Modal analysis is dynamic analysis, and the dynamic problem satisfies the following equilibrium equation:

$$[M]\{x''\}+[C]\{x'\}+[K]\{x\}={F(t)} \quad (1)$$

Where, $[M]$--mass matrix; $[C]$--damping matrix; $[K]$--stiffness matrix; $\{x\}$, $\{x'\}$, $\{x''\}$--displacement vector, velocity vector, acceleration vector; $\{F(t)\}$--force vector.

In this paper, the modal analysis for the ATV under the ideal state is mainly to solve the natural frequency and mode shape. The damping of the structure has little influence on the natural frequency, so the effect of damping can be ignored, so the equation (1) can be simplified as:

$$[M]\{x''\}+[K]\{x\}={0} \quad (2)$$

Each point of the ATV makes simple harmonic motion, and its displacement is a sine function:

$$\{x(t)\}={j}\cos(\omega t) \quad (3)$$

Where, $\omega$--circular frequency; $\{j\}$--amplitude column vector.
From equation (2) (3):

\[(K-\omega^2[M])\{x\} = \{0\}\]  \hspace{1cm} (4)

By solving equation (4), the eigenvalues \(\omega\) and \(\{j\}\) can be obtained, that is, the natural frequencies and mode shapes of each mode of the system\[^7\]. Obtaining the natural frequencies and mode shapes of each mode can intuitively reflect the dynamic characteristics and stiffness characteristics of the ATV in the analysis state.

4.2. External incentive analysis and meshing

In order to avoid the resonance of ATV running, it is necessary to perform an excitation vibration analysis. The external excitation vibration mainly comes from the unevenness of the ground, and the frequency is calculated as:

\[f = \frac{v}{3.6l}\]  \hspace{1cm} (5)

Where, \(v\) --velocity (km/h); \(l\) --wavelength of road roughness (m)

According to the actual situation, when the ATV is running in the mountains, the velocity is related to the wavelength of road roughness. For the terrain with a small wavelength of road roughness, the velocity is generally less than 26 km/h, then the wavelength of road roughness \(l = 0.58\) m, with \(\omega\) into the above formula, \(f = 12.45\) Hz. Therefore, the first natural frequency is at least 13 Hz to avoid road undulations that cause resonance\[^8-9\].

A hexahedral meshing model with simplified formalization and consistent material properties with static analysis is established, and modal analysis is performed under prestress.

4.3. Model solution analysis

The dynamic characteristics of the structure mainly depend on the low-order mode shapes\[^10\]. The non-zero first 3 modes results and the mode shape nephogram are extracted, and the corresponding models are arranged correspondingly to facilitate the visual observation of the mode shape.

From Fig.6 to Fig.9, the frequency shows an increasing trend, and the mode shape is greater than 13 Hz, without resonance phenomenon. There is no obvious deformation of the structure in each mode in Fig.6; from Fig.7 to Fig.9, the frequency and mode shape of the same mode are almost the same: 1st mode, the mode shape is mainly manifested as the upward bending without obvious torsion of the frame, the front CArms and TArms have large displacement changes, and the obvious forward tilt of the ATV; 2nd mode, the mode shape is mainly manifested as the downward bending of the frame, and the front and rear of the ATV converges towards the middle, with slight torsion, and the CArms and TArms are slightly offset; 3rd mode, the mode shape is mainly manifested as obvious torsion deformation and slight bending deformation of the frame, and the front torsion is obvious, and it is biased to the outer side of the extreme turn and the lower side of off-road running. In general, the frame deformation is more serious, accompanied by bending and torsion deformation, followed by the deformation and offset of the Beams, CArms, and TArms.

![Fig.6 The first 4 modal nephogram of run straight on horizontal road](image)

\[\begin{align*}
&\text{a 1st 13.672Hz} \\
&\text{b 2nd 15.313Hz} \\
&\text{c 3rd 17.072Hz}
\end{align*}\]
5. Conclusion

By analyzing the results of static simulation and modal simulation of the ATV, the deformation of the frame is the most serious. Although the frame structure meets the strength requirements, its structure is simple, and the connection between the front and rear of the vehicle is relatively simple, resulting in insufficient resistance to deformation, which is the weakest part of the ATV structure design. The modal analysis results show that the displacement of Beams, CArms, TArms and other components is caused by the deformation of the frame, but the deformation itself is not very large.

1) The axle of the ATV is subject to the greatest stress during extreme off-road turns, and the frame is severely deformed, which provides direction for maintenance.

2) The analysis of modal vibration characteristics shows that the frame has large bending and torsion deformation, and the deformation caused by the insufficient stiffness of the frame provides a theoretical basis for the optimal design of the ATV.

3) The vibration frequency of the ATV modal analysis under different working conditions is obtained, which provides a reference for the matching of topography and driving velocity, and the design of control system.
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References
[1] Moroney P, Doyle M, Mealy K. (2003) All-terrain vehicles-unstable, unsafe and unregulated: A prospective study of ATV-related trauma in rural Ireland. Injury, 34(3):203-205.
[2] Zhou F. (2014) Structural design and characteristic analysis of a new all-terrain mobile platform. National University of Defense Technology, Changsha.
[3] Chen X, Lou W, Jiang Y, et al. (2015) Static and Dynamic Performance Analysis and Lightweight Design of ATV Frame. Journal of Chongqing University of Technology, 29(2):1-6.
[4] Huang Z. (2016) ANSYS Workbench 16 Super Learning Manual. Posts&Telecom Press, Beijing.
[5] Han H, Zhou Y, et al. (2019) Height Adjustment Design and Finite Element Analysis of Wine Grape Pruning Machine. Journal of Agricultural Mechanization Research, 41: 37-41+97.
[6] Qu L G, Pan K Q, Chen X. (2010) Modal Analysis of Flexible Assembling Fixture for Aircraft Panel Component. Advanced Materials Research, 97-101:3392-3396.
[7] Saeed M. (2015) Finite Element Analysis--ANSYS Theory and Application. Publishing House of Electronics Industry, Beijing.
[8] Wang J, Bai H, Sun X, et al. (2019) Design and Dynamic Analysis of Spray Device for Paddy Field Sprayer. Transactions of the Chinese Society for Agricultural Machinery, 50(3):69-79.
[9] Wang Y, Yu X, Cao W. (2011) Design, static and modal analysis of a electronica car body. Automobile Applied Technology, 7:50-53.
[10] Fu Z. (1990) Vibration mode analysis and parameter identification. China Machine Press, Beijing.